



Air Force Research Laboratory



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AFRL Research in Plasma-Assisted Combustion

23 October 2013

***Cam Carter & Tim Ombrello
With input from Bish Ganguly and
Steve Adams***

**Aerospace Systems Directorate
Air Force Research Laboratory**

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Overview

Research within My Division



***Focus on hypersonic flight:
scalability, performance, operability***

Research Includes...

- *Extramural* programs such as
 - *SJ Engine Demonstrator, X-51*
 - *HIFiRE: US-Aus. flight-test program*
- *In-house* programs on
 - *Scramjet propulsion*
 - *Non-equilibrium flows*
 - *Diagnostics for scramjet controls*
 - *Boundary-layer transition*
 - *Structural sciences for hypersonic vehicles*
 - *Computational sciences for hypersonic flight*



**X-51A – Flight 4: May 1, 2013
Achieving M-5.1 flight**



Overview

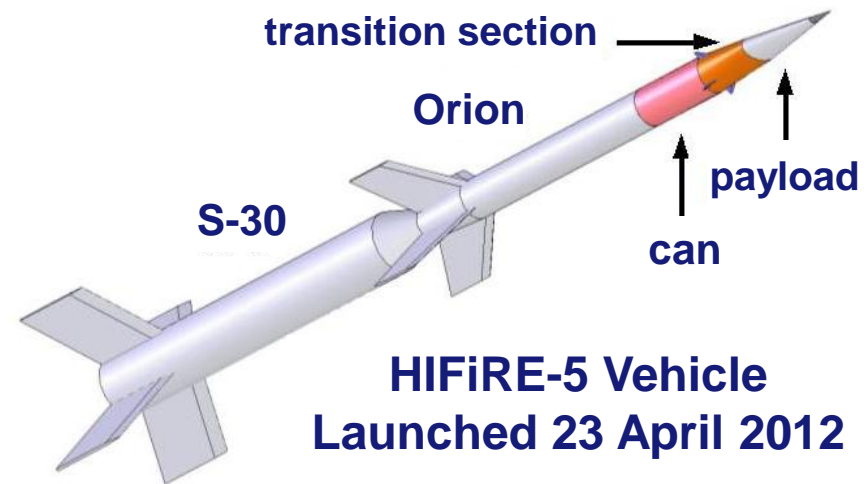
Research within My Division



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 - *Computational sciences for hypersonic flight*



**HIFiRE-5 Vehicle
Launched 23 April 2012**



Overview



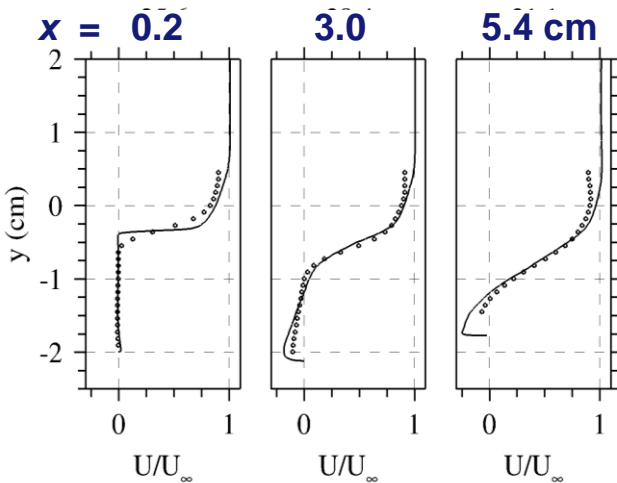
- A few highlights not covered today (in lovely quad-chart fashion), showing broad focus of basic research program
- Specific Focus
 - Bish Ganguly's research: *Role of Sub-Breakdown E-Fields on flames*
 - Steve Adams' research: *REMPI-Assisted Gas Breakdown*
 - Our work: *Flame Speed Enhancement (by O_3)*



Overview

Highlights of Basic Research Program

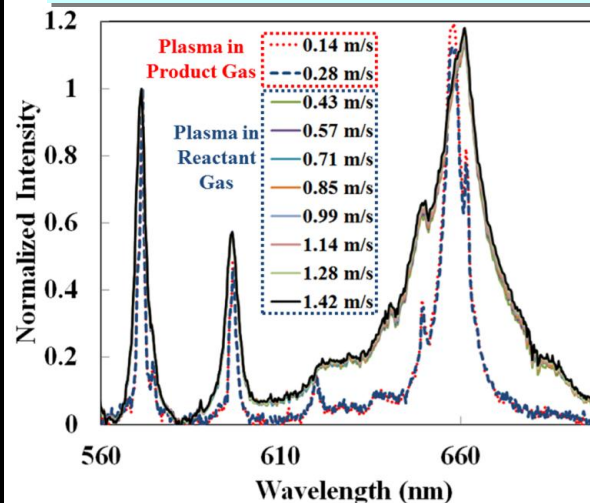
RANS-LES Simulations of Cavity Flowfield



**Peterson (NRC);
Tuttle (NRL);
Hagenmaier**

Comparison with
Tuttle-PIV dataset
(nonreacting
shown here)

Laser-Induced Breakdown Spectroscopy

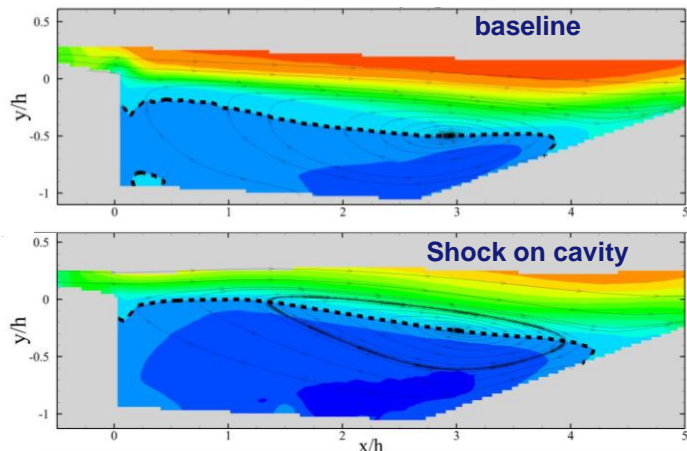


Do (Notre Dame)

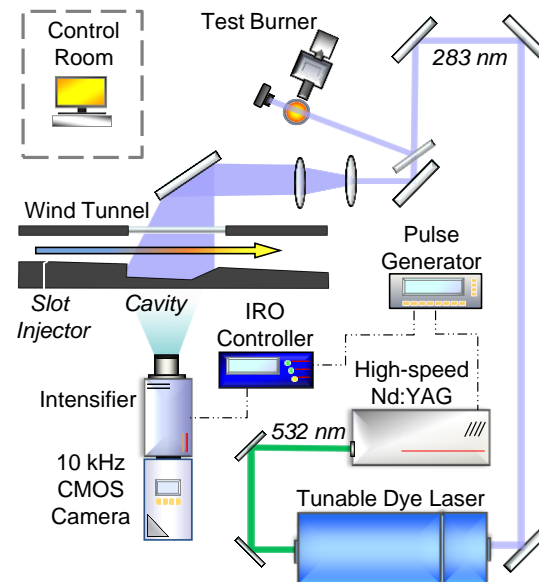
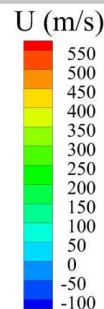
Measurements in
reacting and
nonreacting flows;
**now applied in
cavity flowfield**

Inlet Distortion Effects on Cavity Flowfield

Goyne, Kirik (UVA); Peltier (NRC); Hagenmaier



Mean axial
velocity



**kHz Imaging for
Cavity
Flameholding**

**Hammack, Lee (UI);
Hsu**

Setup for OH
PLIF



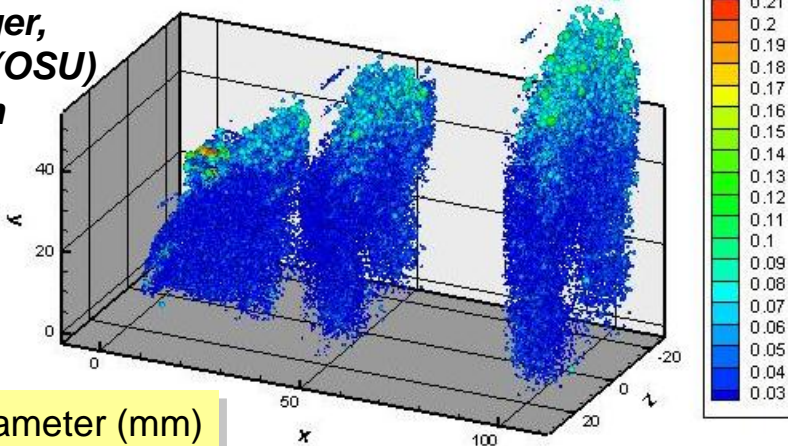
Overview

Highlights of Basic Research Program



Digital Holography for Aerated Sprays

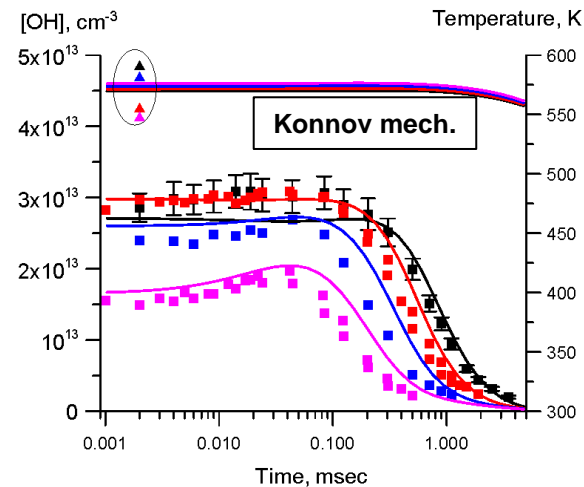
Olinger,
Sallam (OSU)
Lin



Drop diameter (mm)
in crossflow

OH & T in a Repetitively Pulsed Ns Discharge

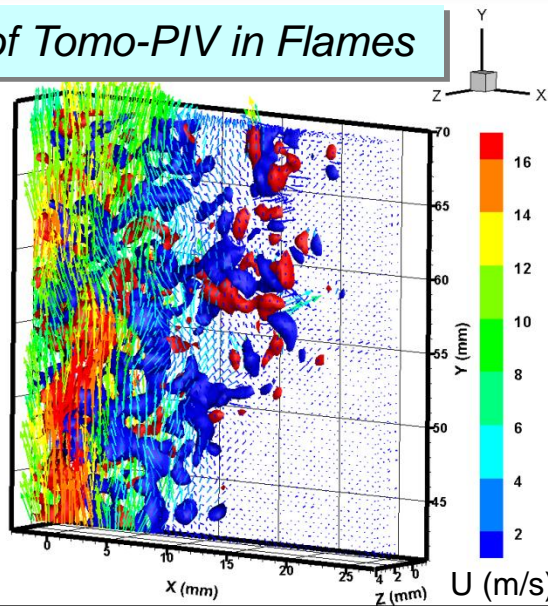
Yin, Montello,
Adamovich,
Lempert (OSU)



Measurements vs.
kinetics calcs.

Study of Efficacy of Tomo-PIV in Flames

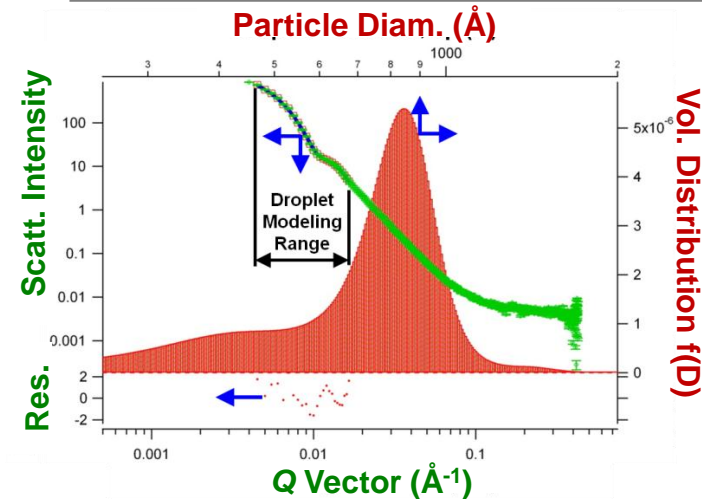
Boxx, Meier (DLR)



Application to
lifted jet flame

Supercritical C₂H₄ Injection: Drop Sizing

Zuo (ANL);
Lin



Small-angle
x-ray scatt.
(SAXS)



Role of Sub-Breakdown E-Fields in Modifying Flame Kinetics & Fluidics



Objective: Study dynamics of laminar flame with applied sub-breakdown, pulsed E-field

Payoff: Potential for improved flameholding/efficiency in AF combustors

Progress:

- Dynamics studied with kHz-rate imaging (both chemiluminescence imaging and particle image velocimetry, PIV)
 - Relatively small amount of electrical power can cause an otherwise steady, laminar flame to highly unsteady behavior
- Flame thickness quantified, via OH/acetone planar laser-induced fluorescence, showing substantial increase
- Flame recovery mechanism after (applied voltage) is fluidic in nature



Role of Sub-Breakdown E-Fields

Background



- Direct experimental evidence & robust modeling of exact mechanism by which sub-breakdown E-field modifies flame fluidics/kinetics lacking
 - Liftoff and blowoff limits of flames in AC/DC field by Kim *et al.*
 - Relationship between burning velocity and imposed current through thermal power release and/or direct chemical reaction rate for DC fields by van den Boom *et al.*
 - Electric field control of small capillary diffusion flames has been explored by Borgatelli *et al.*
- Numerical model by Starikovskii *et al.* suggests that weak E-fields influence areas with a charged particle density gradient

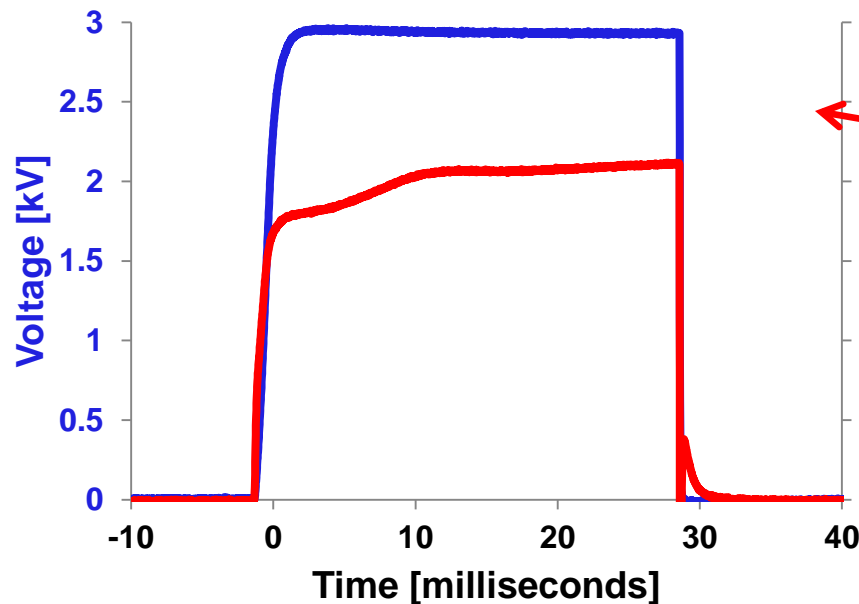


Role of Sub-Breakdown E-Fields

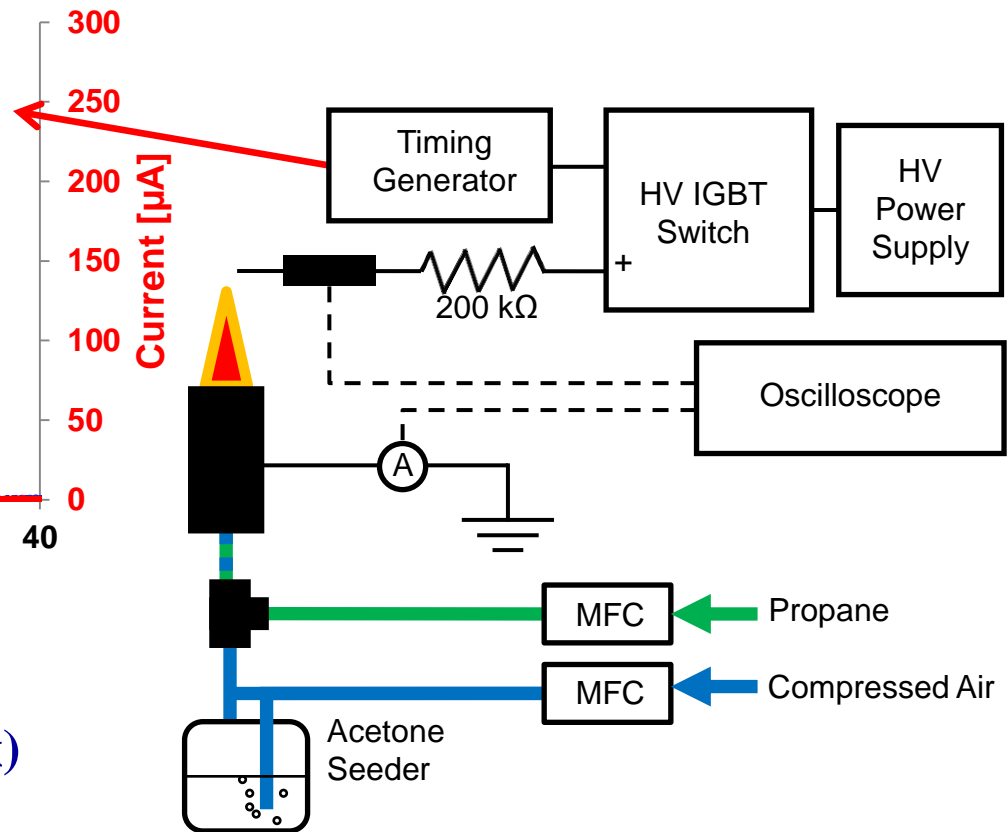
Experimental Setup: Flame & V/I



Typical Voltage and Current



- 30 ms in duration @ 10Hz
- 3 kV, 200 μA , 0.25 Watt (max)



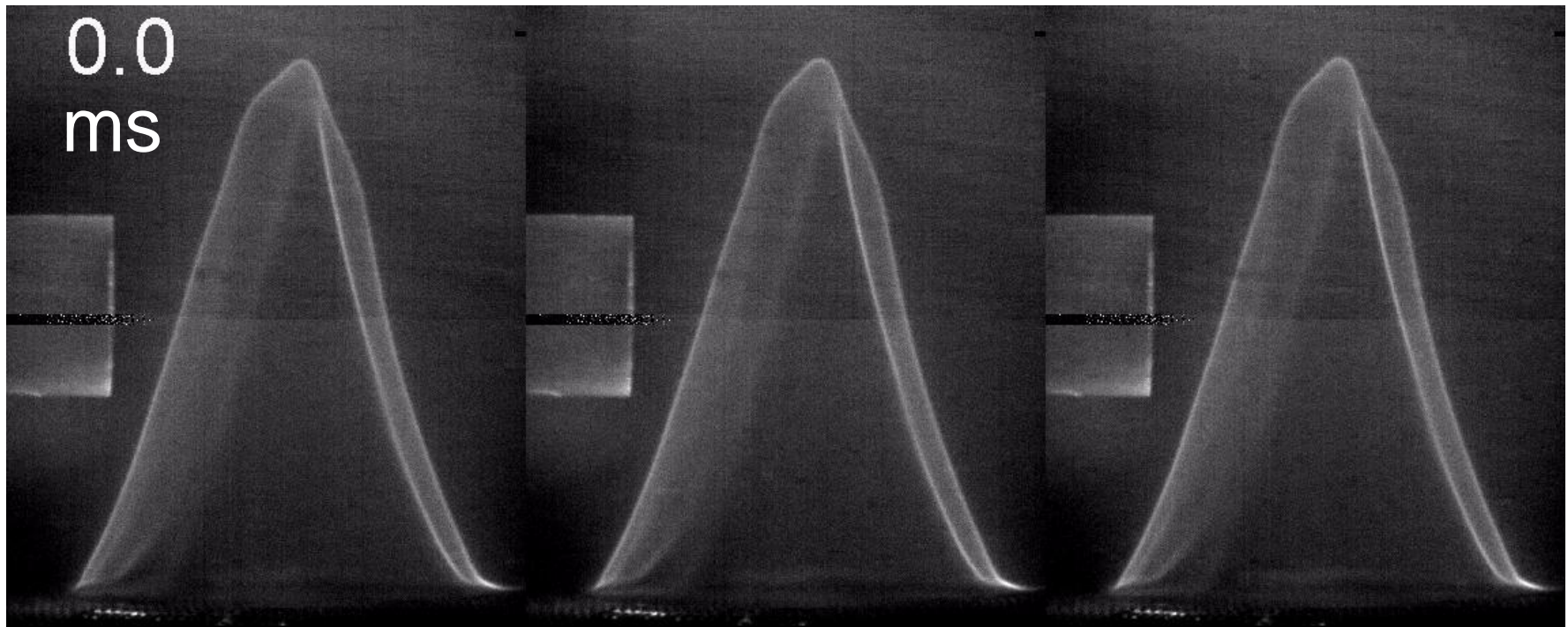


Role of Sub-Breakdown E-Fields

High-speed Imaging



Image sequences exemplify flame fluctuations and repeatability of process



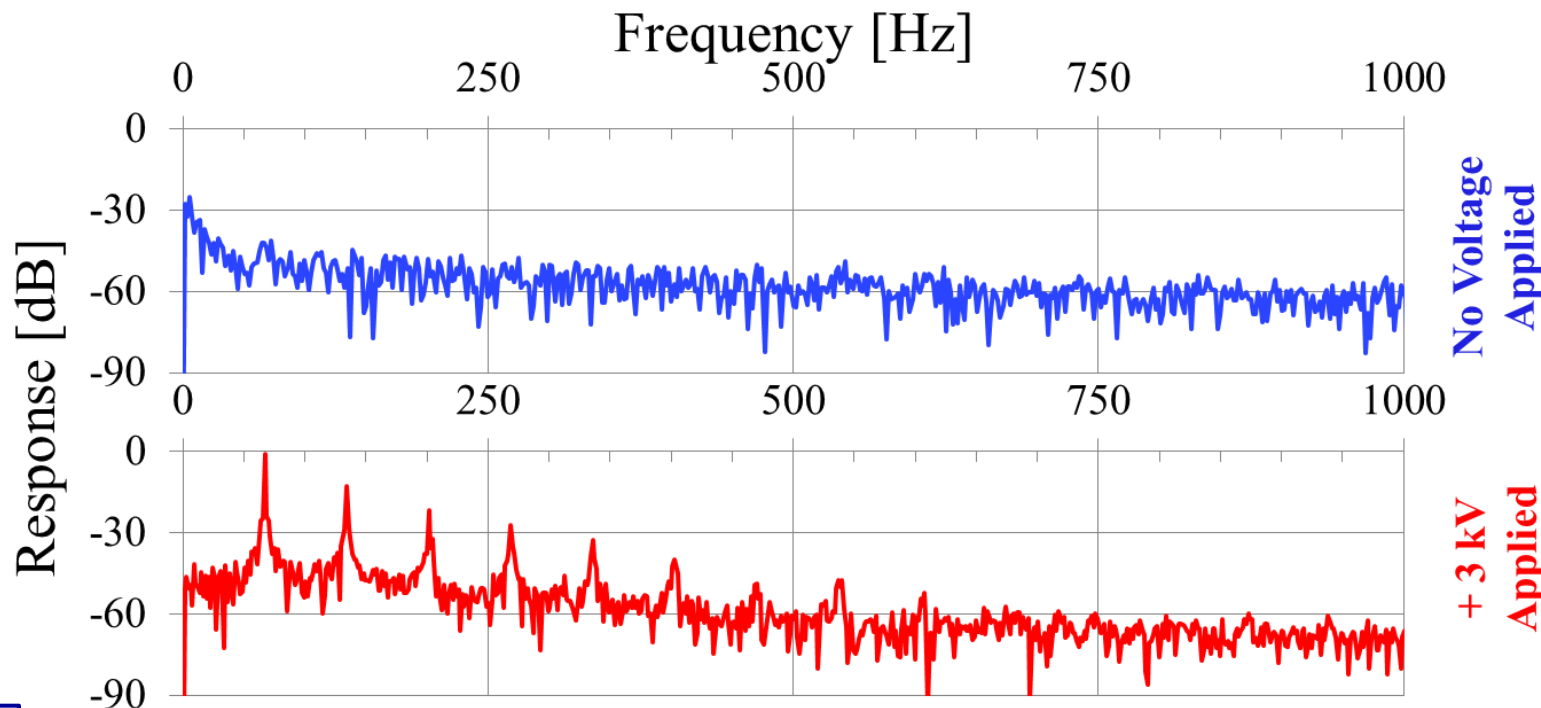


Role of Sub-Breakdown E-Fields

Frequency Spectrum



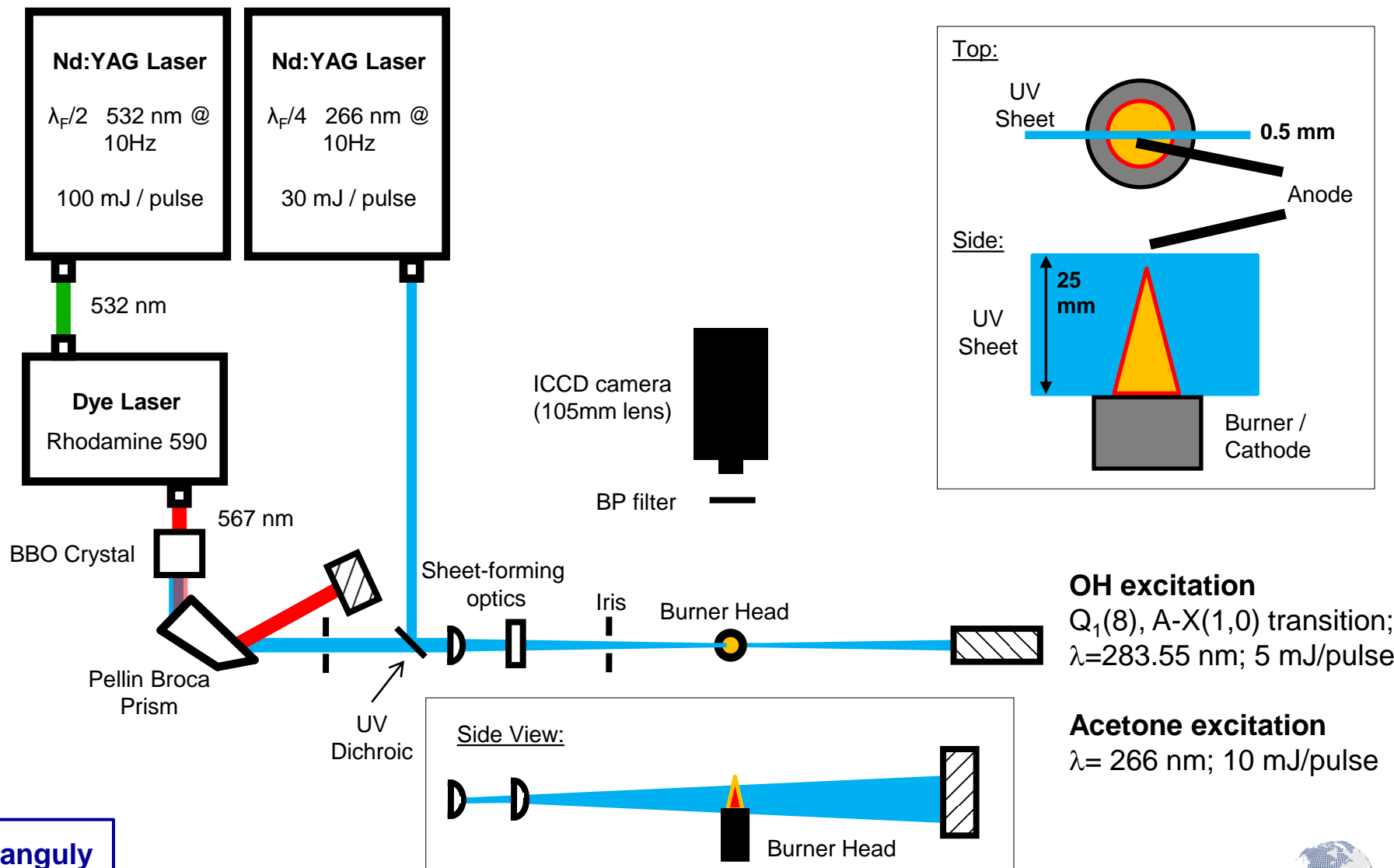
- FFT of recorded current traces to show the dominant frequencies of the induced perturbation process
 - Current used due to high sensitivity to conductivity and therefore overall flame shape (compared to OH/OH*/broadband emission)





Role of Sub-Breakdown E-Fields

Experimental Setup: PLIF



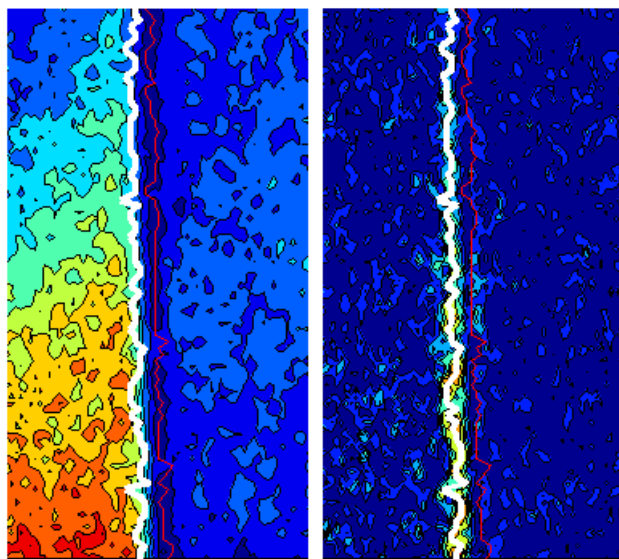
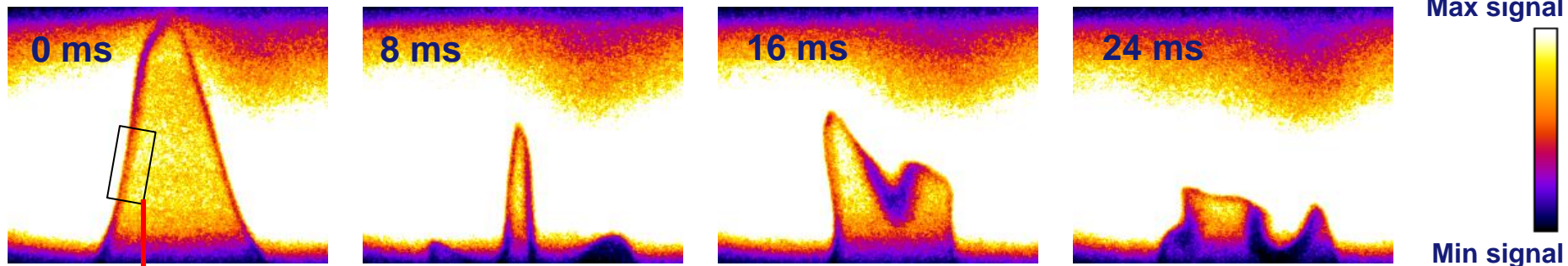


Role of Sub-Breakdown E-Fields

PLIF Results



Combined OH & Acetone PLIF Images



S_{LIF}

$\partial S_{LIF} / \partial x$

- Algorithm finds gradients of S_{LIF}
- Reaction zone thickness (δ between gradient locations) normal to local flame shape
- Iterative process finds reaction zone to be 0.6 to 0.8 mm for unperturbed laminar flame
 - much larger for perturbed flame



REMPI-Assisted Gas Breakdown

Steve Adams, et al.



Objectives:

- Investigate Resonance-Enhanced Multi-Photon Ionization, REMPI, assisted laser gas breakdown
- Reduce breakdown voltage along laser path
- Guide laser and spark into fuel rich volume
- Determine effects of fiber optic coupling

Payoff:

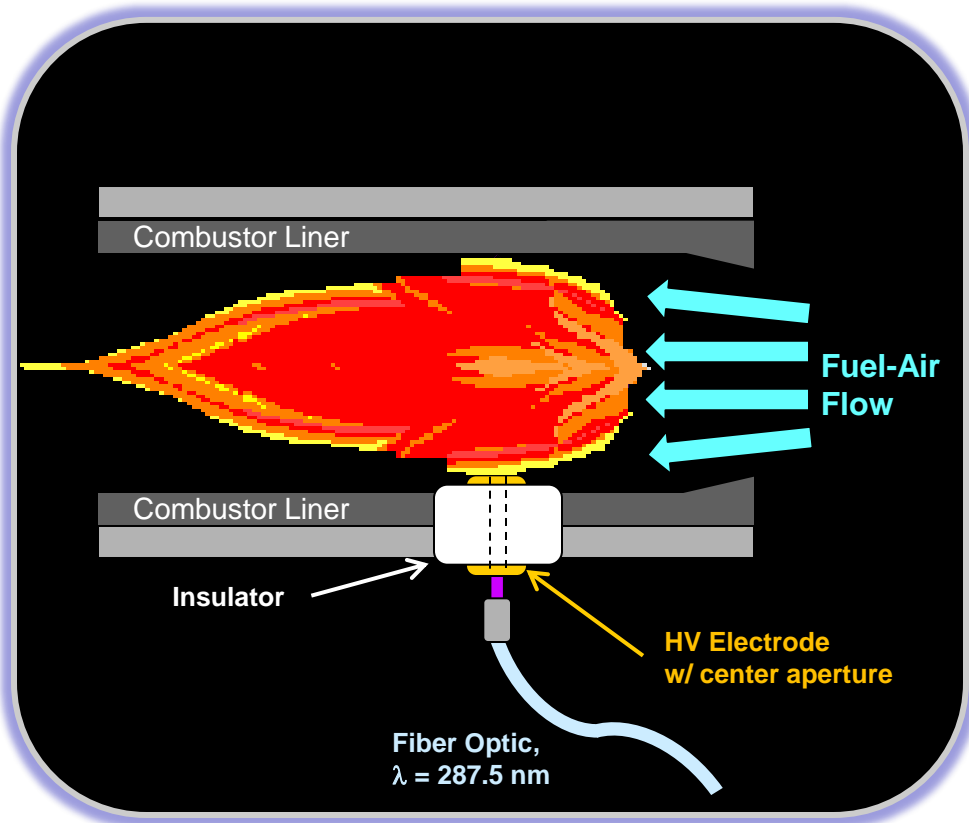
- Potential for ignition away from walls/surfaces
 - Quasi-volumetric (or at least 1-D) ignition
- Potential for increased reliability of relight for engine flame-out

Progress:

- Ignition demonstrated in simple flows
- Resonant laser is advantageous in inducing air breakdown
- Photoionization of fuel closes the gap (for ignition) between *resonant* and off-resonant laser performance



REMPI-Assisted Breakdown Concept



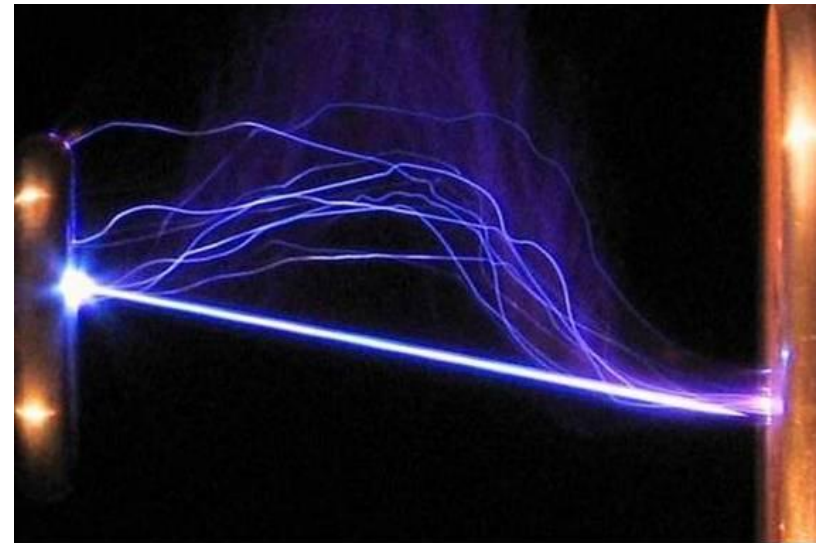
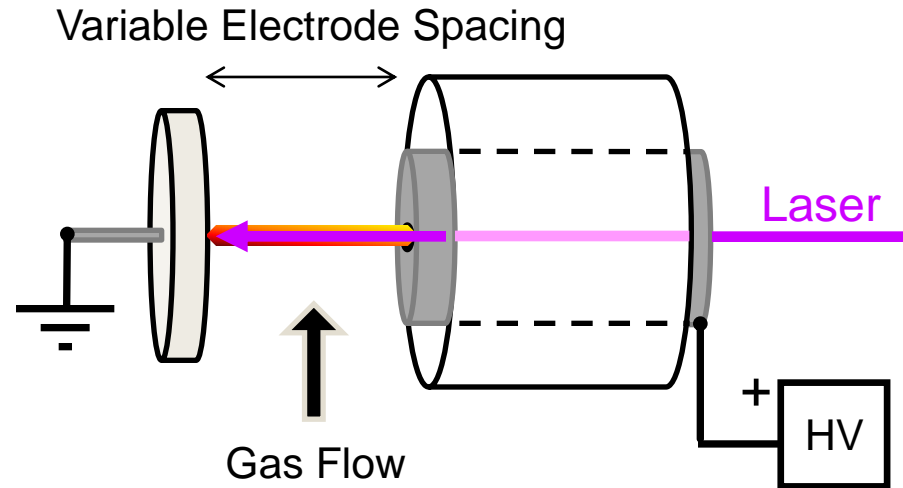
- Resonance-enhanced multi-photon ionization (REMPI) with UV laser pulse creates *pre-ionized* path
- High voltage applied: *spark is guided along pre-ionized path*
- High reliability of ignition within fuel-rich region
 - Ignition away from walls



REMPI-Assisted Gas Breakdown

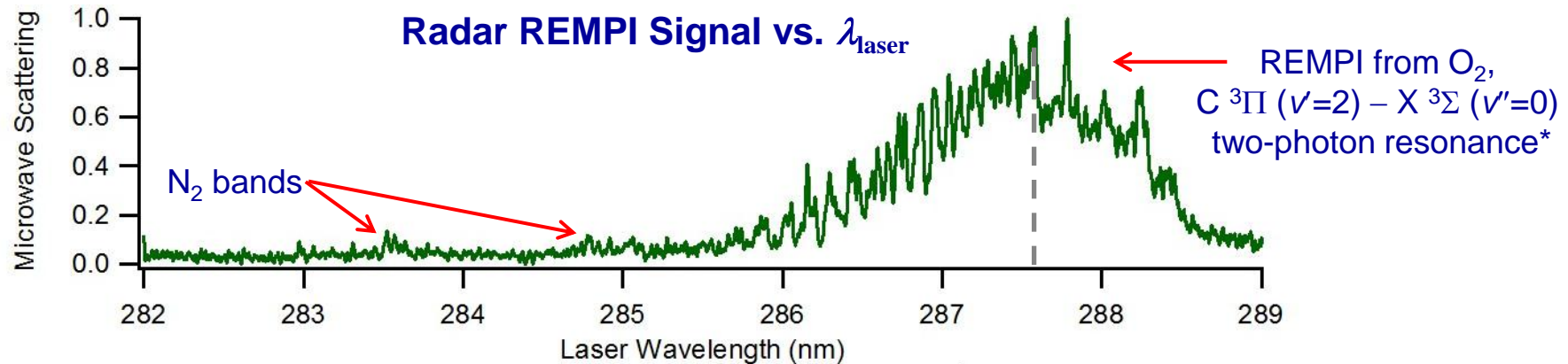


- Laser sent through aperture in high voltage electrode
- Breakdown and arc follow laser pulse along pre-ionized path
- Arc-path follows laser *pre-ionization* path, even when laser is angled compared to applied electric field

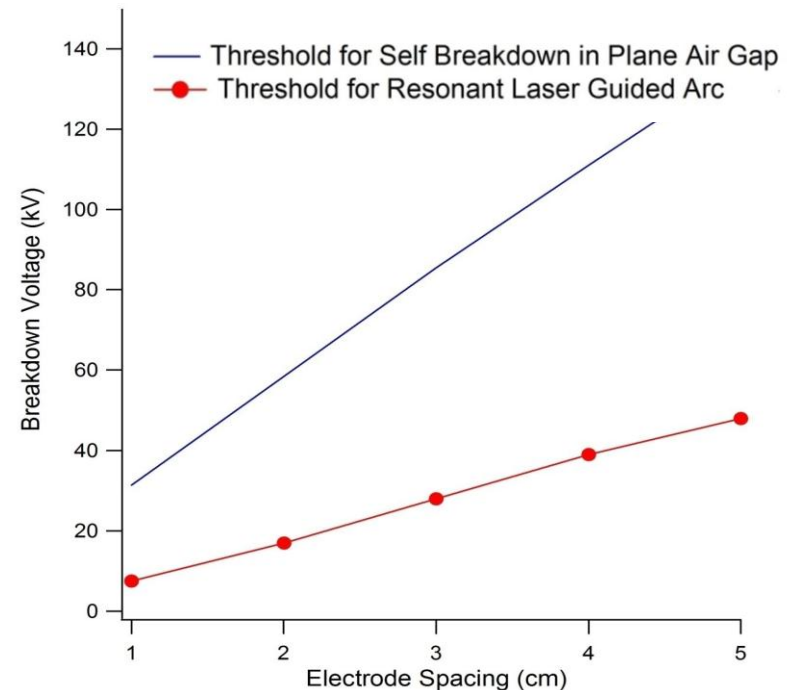




REMPI-Assisted Gas Breakdown



- Use Radar-REMPI (in air) to characterize induced electron concentration vs. λ_{laser}
- Use $\lambda_{\text{laser}} = 287.5\text{ nm}$ (~max e concentration) for *resonant* & 266 nm for *nonresonant* comparison
 - *resonant* threshold is ~1/3 of theoretical air self-breakdown



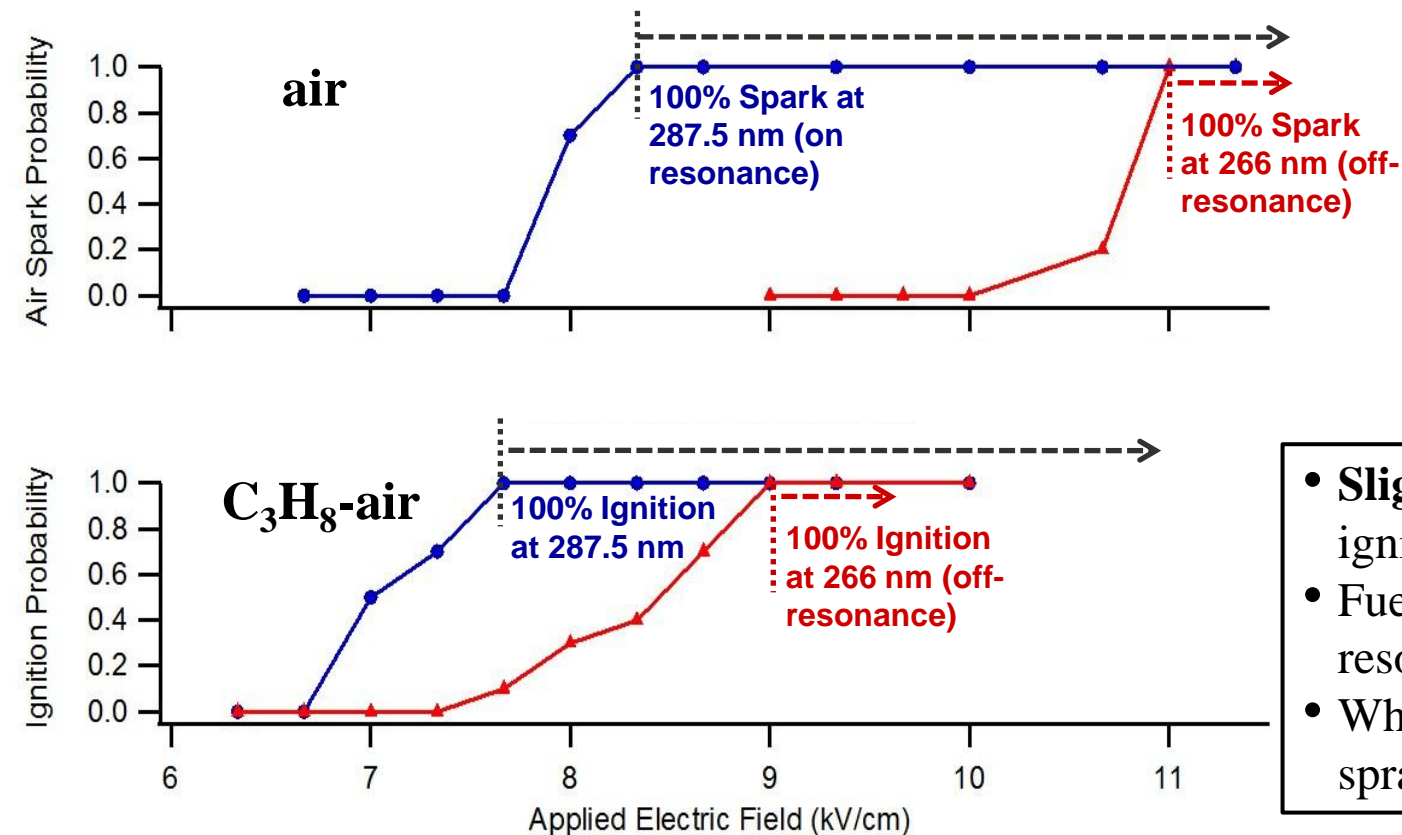


REMPI-Assisted Gas Breakdown

Resonant vs. Nonresonant UV Excitation



- Now compare spark/ignition with laser resonance ($\lambda_{\text{laser}} = 287.5 \text{ nm}$) vs. nonresonance ($\lambda_{\text{laser}} = 266 \text{ nm}$) in air/ C_3H_8 -air



- Much** lower E-field threshold to create spark

- Slightly** lower threshold for ignition
- Fuel tends to enhance non-resonant breakdown effects
- What about effects with fuel sprays?



Flame Speed Enhancement by O_3



Objective: Study effect of plasma-derived species on flame speed enhancement

Payoff: Increased flame propagation speeds in AF combustors, particularly high-speed combustors

- Potentially more robust flame stabilization & improved ignitability

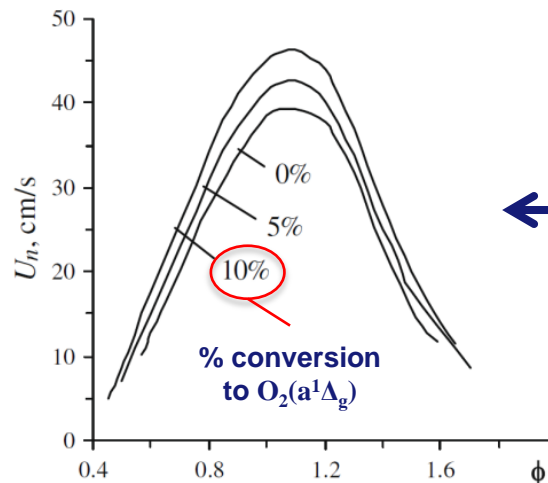
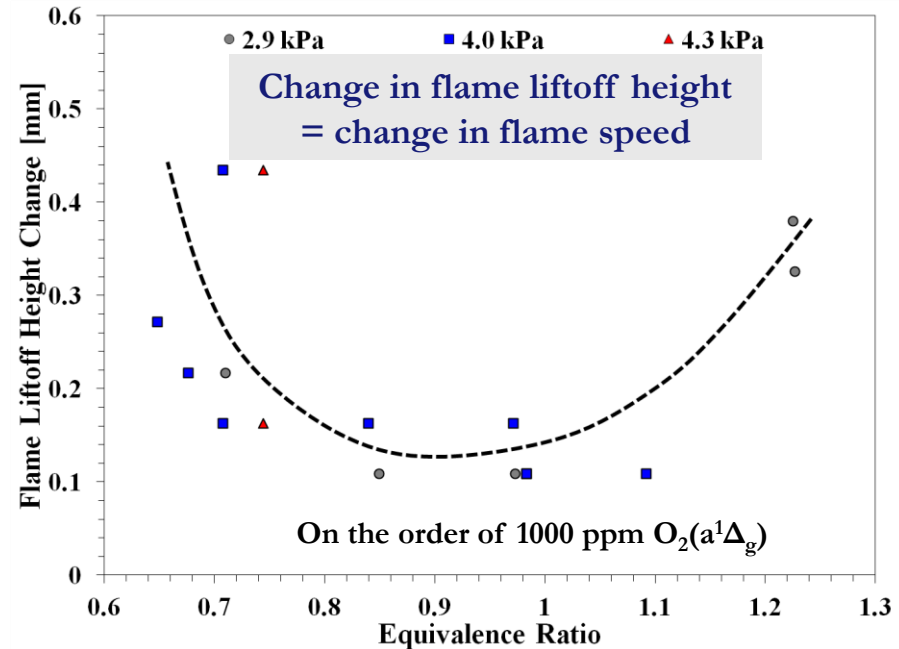
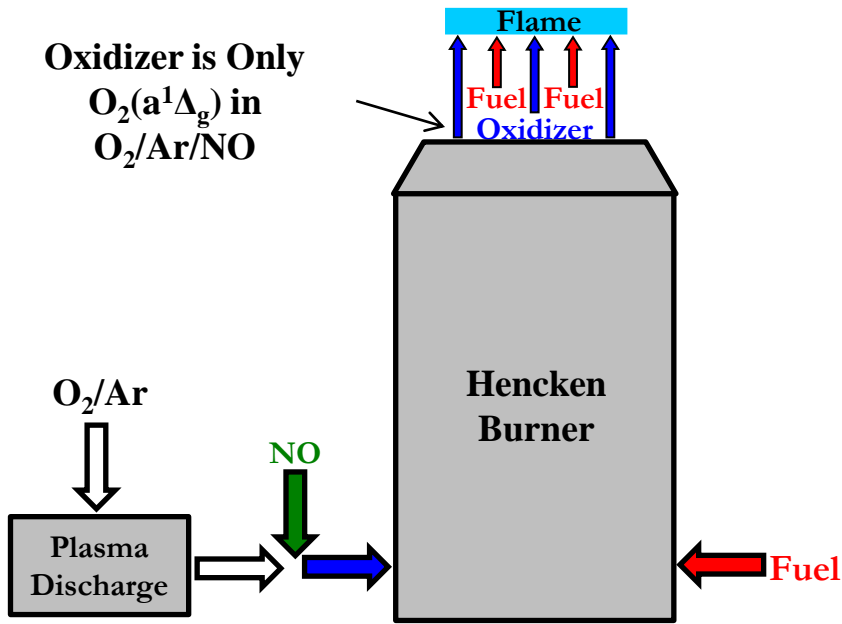
Progress:

- Characterization of O_3 enhancement (flame speed) for C_2H_4 flames
 - working on measurements with liquid fuels
- Initial tests within cavity flameholder in M-2 crossflow: infer flame speed enhancement during ignition transient



Flame Speed Enhancement by O_3

Past Efforts: $O_2(a^1\Delta_g)$ flame speed enhancement

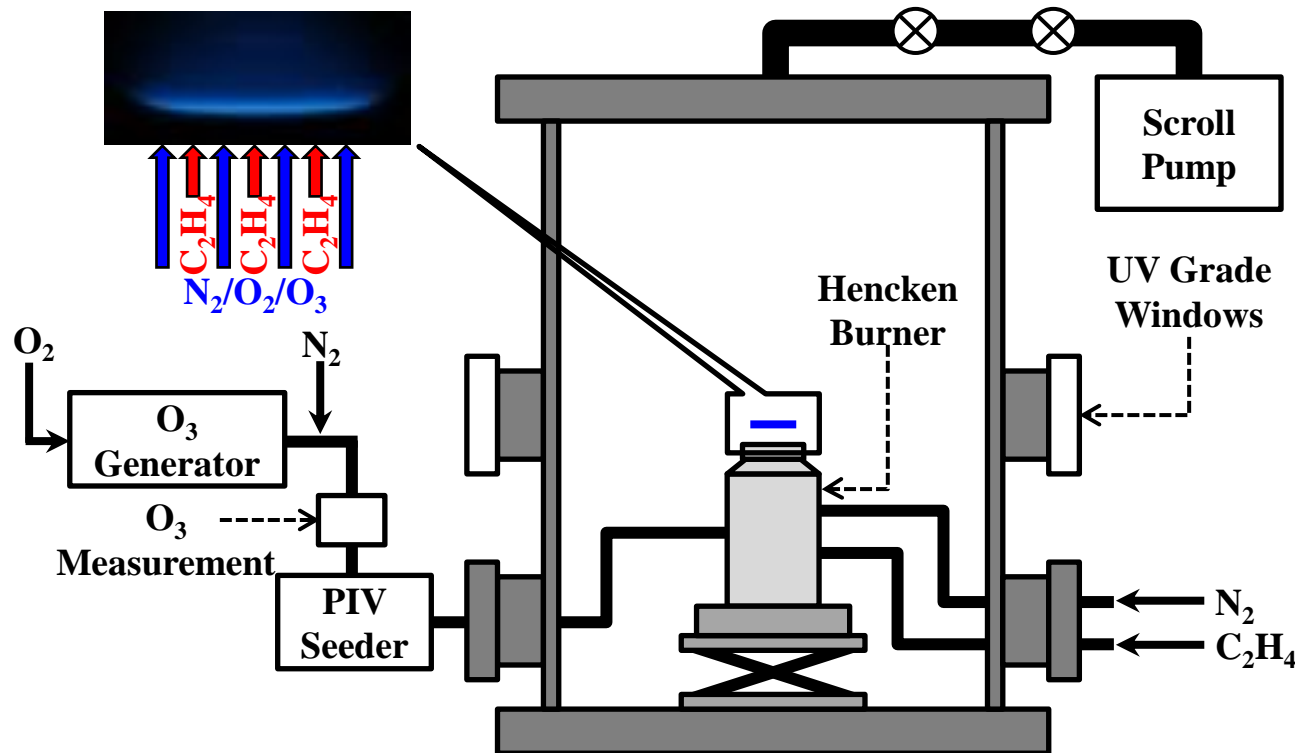


Dependence of enhancement on ϕ , following other predictions: CH_4 -air, Starik *et al.* (Combust. Flame 2010)



Flame Speed Enhancement by O_3

Experimental Setup: Low-Pressure Chamber



- Used alumina particles for particle image velocimetry (PIV)
 - Confirmed that particles do not quench O_3
- Measured flame speeds and enhancement with high accuracy vs. stretch rate

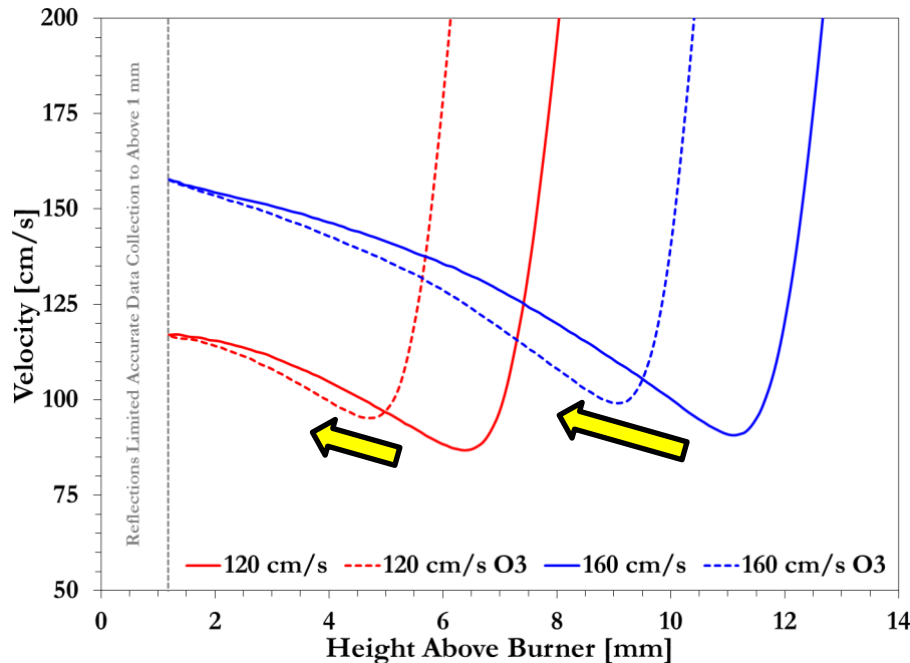


Flame Speed Enhancement by O_3

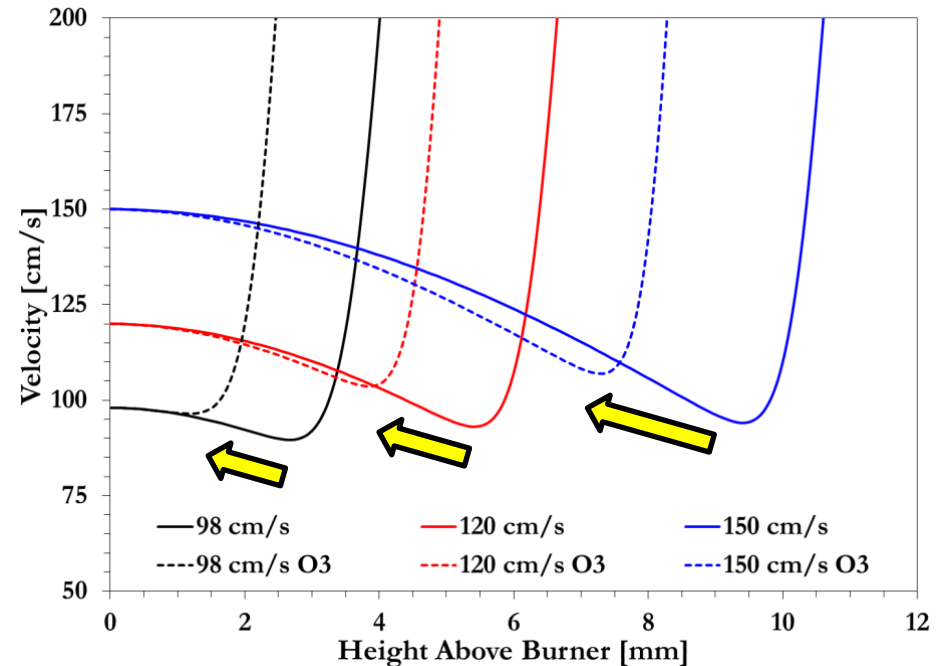
Measurement vs. Computational Results



Measurement



2-D Simulations



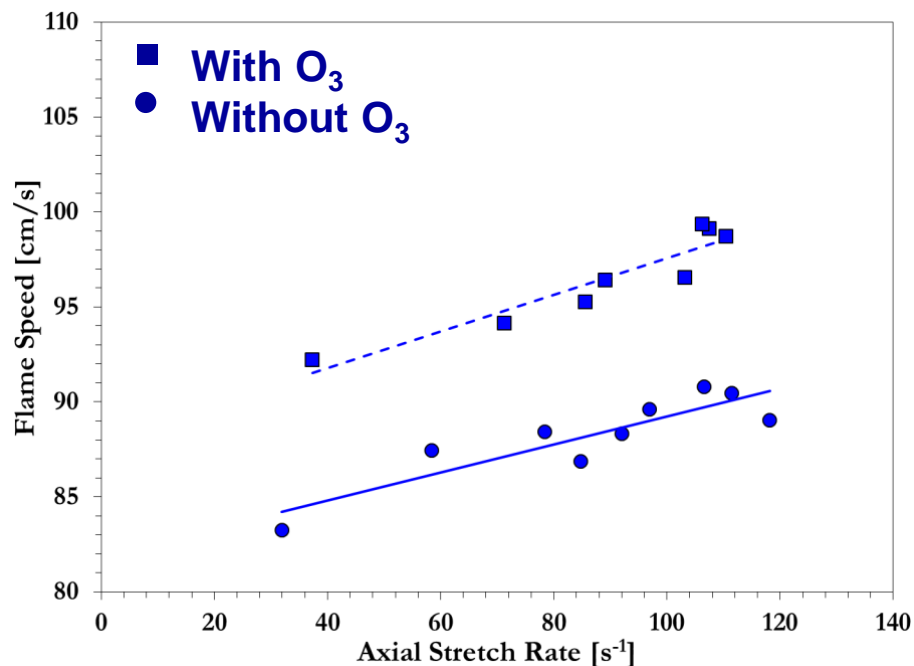
Conditions:

- Equivalence ratio $\Phi = 1$
- O_3 concentration $X = 12,500$ ppm (in *air* mix)

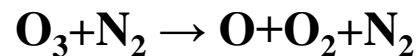
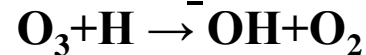


Flame Speed Enhancement by O_3

Flame Speed vs. Stretch Rate



Primary O_3 Reactions



Sensitivity Analysis

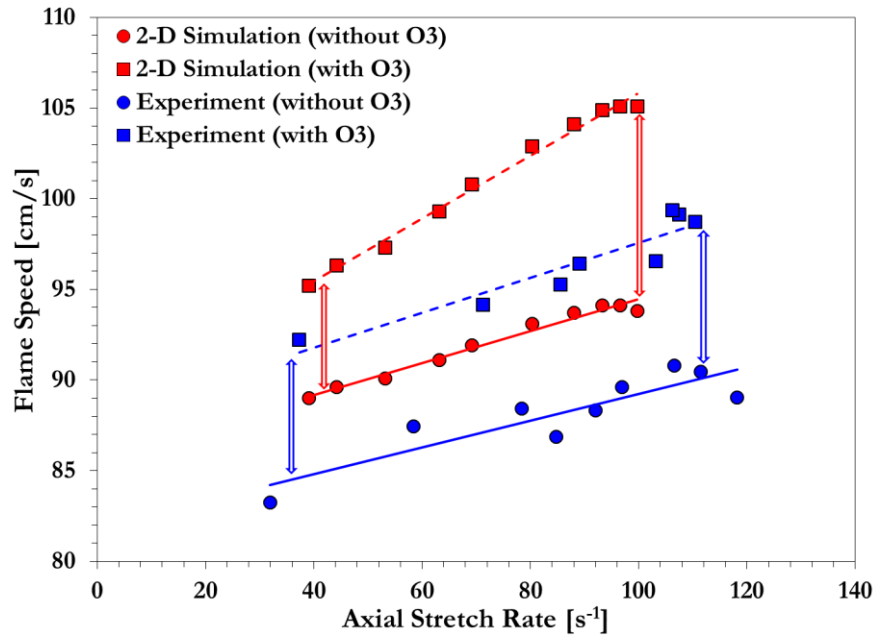
inhibits S_L

enhances S_L



Flame Speed Enhancement by O_3

Trend vs. Stretch Rate



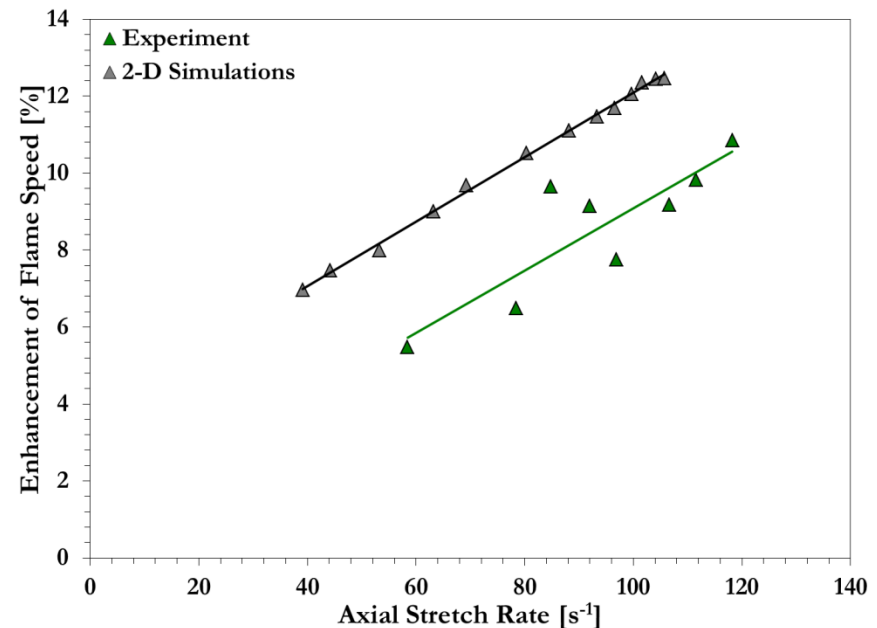
**Flame speed enhancement increases
with increasing stretch rate**

Doubling stretch rate



**Doubling of flame
speed enhancement**

**Model over-predicts absolute flame speeds
and enhancement, but trend is correct**



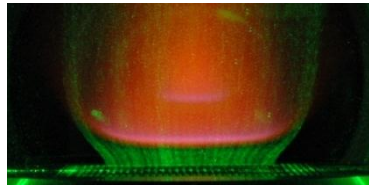


Flame Speed Enhancement by O_3

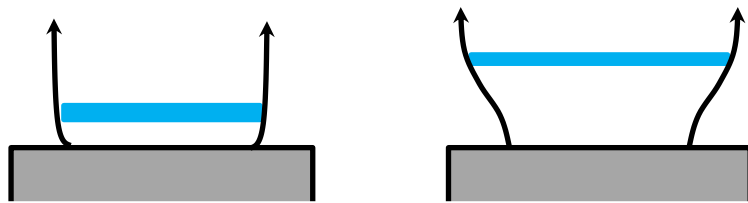
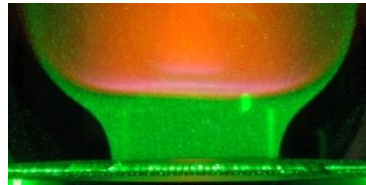
Why Does Flame Speed Increase?



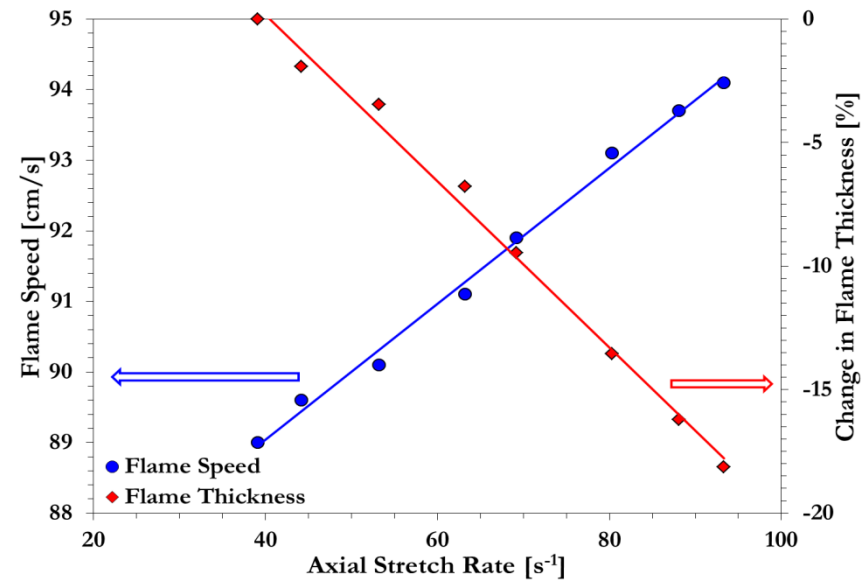
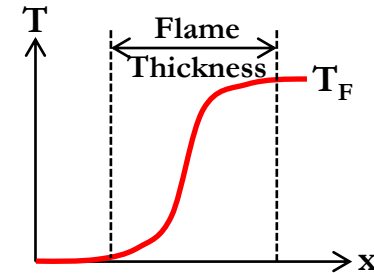
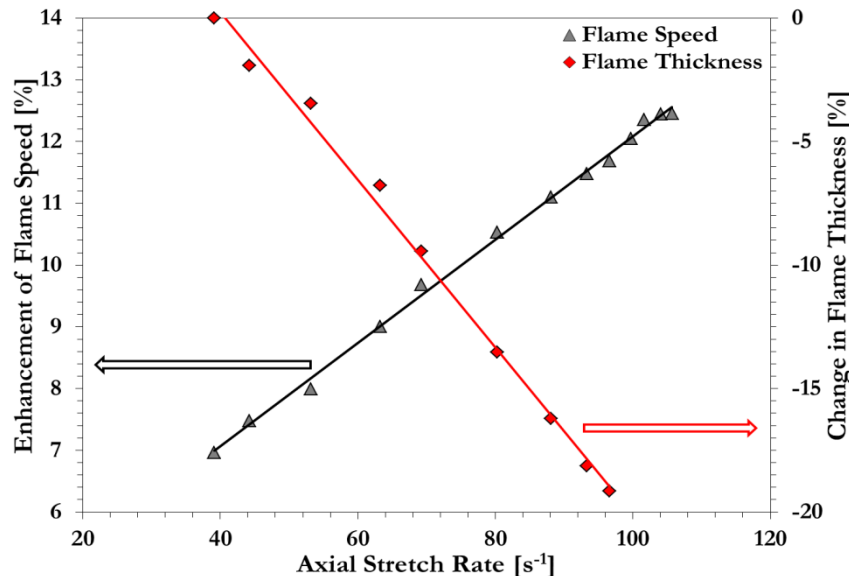
low velocity/stretch rate



high velocity/stretch rate



Decreasing flame thickness



Enhancement of flame speed follows trend of change in flame thickness



What's Next?

Why not try to enhance ignition in the flameholder of a highspeed crossflow?

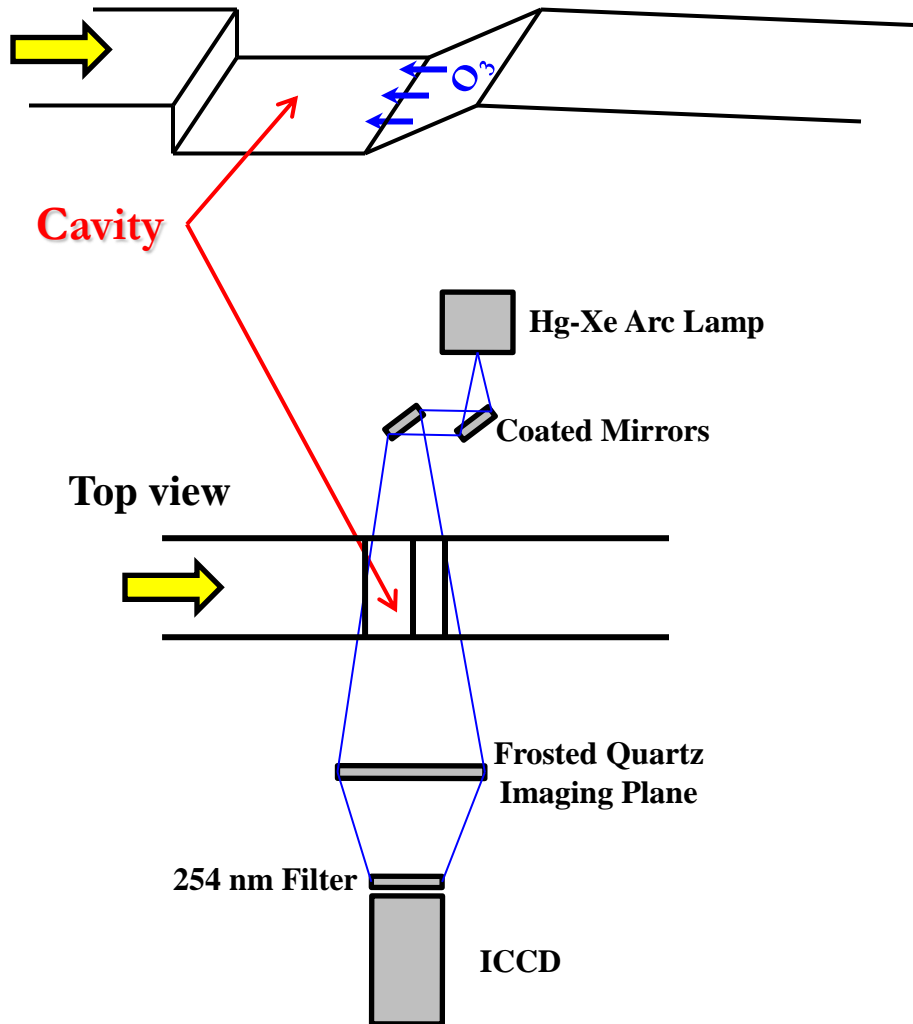


Flame Speed Enhancement by O_3

Effect of O_3 in Cavity – in M-2 Crossflow



O_3 absorption imaging: integrated view of concentration across cavity

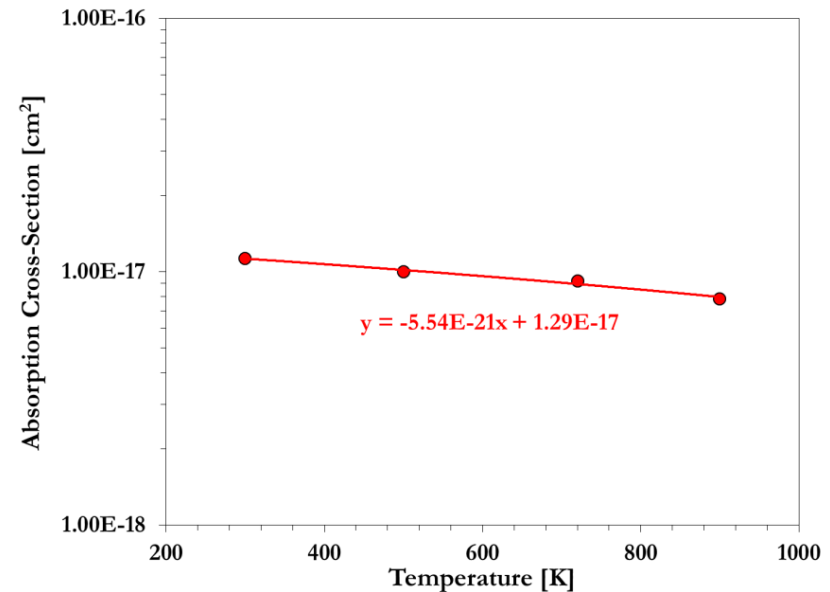


M-2 Crossflow

$$P_{\text{cavity}} = 65 \text{ kPa}; T_{\text{cavity}} = 550 \text{ K}$$

Absorption cross section

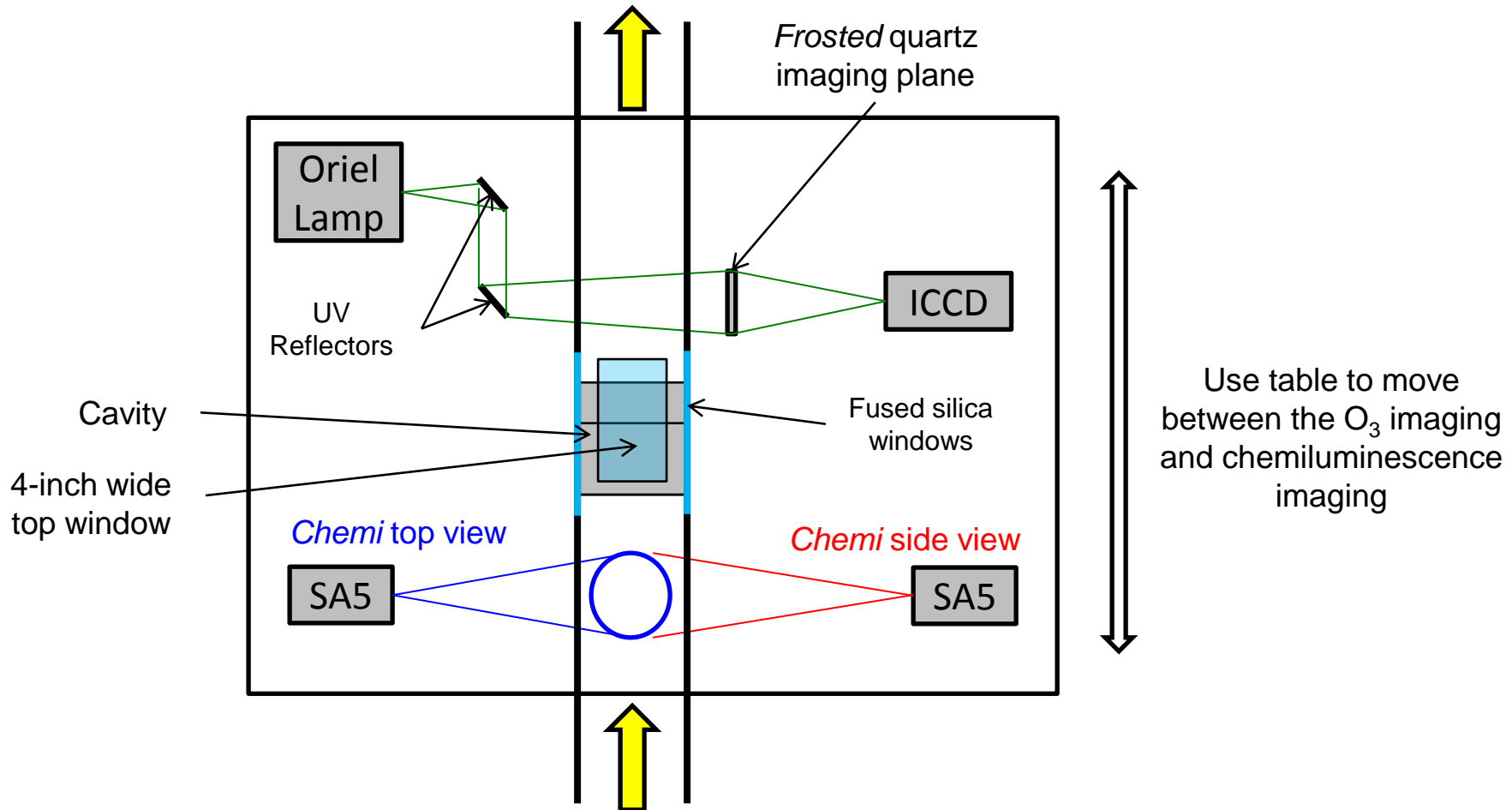
Astholtz, et al., J. Phys. Chem. 1982





Flame Speed Enhancement by O_3

Effect of O_3 in Cavity – in M-2 Crossflow

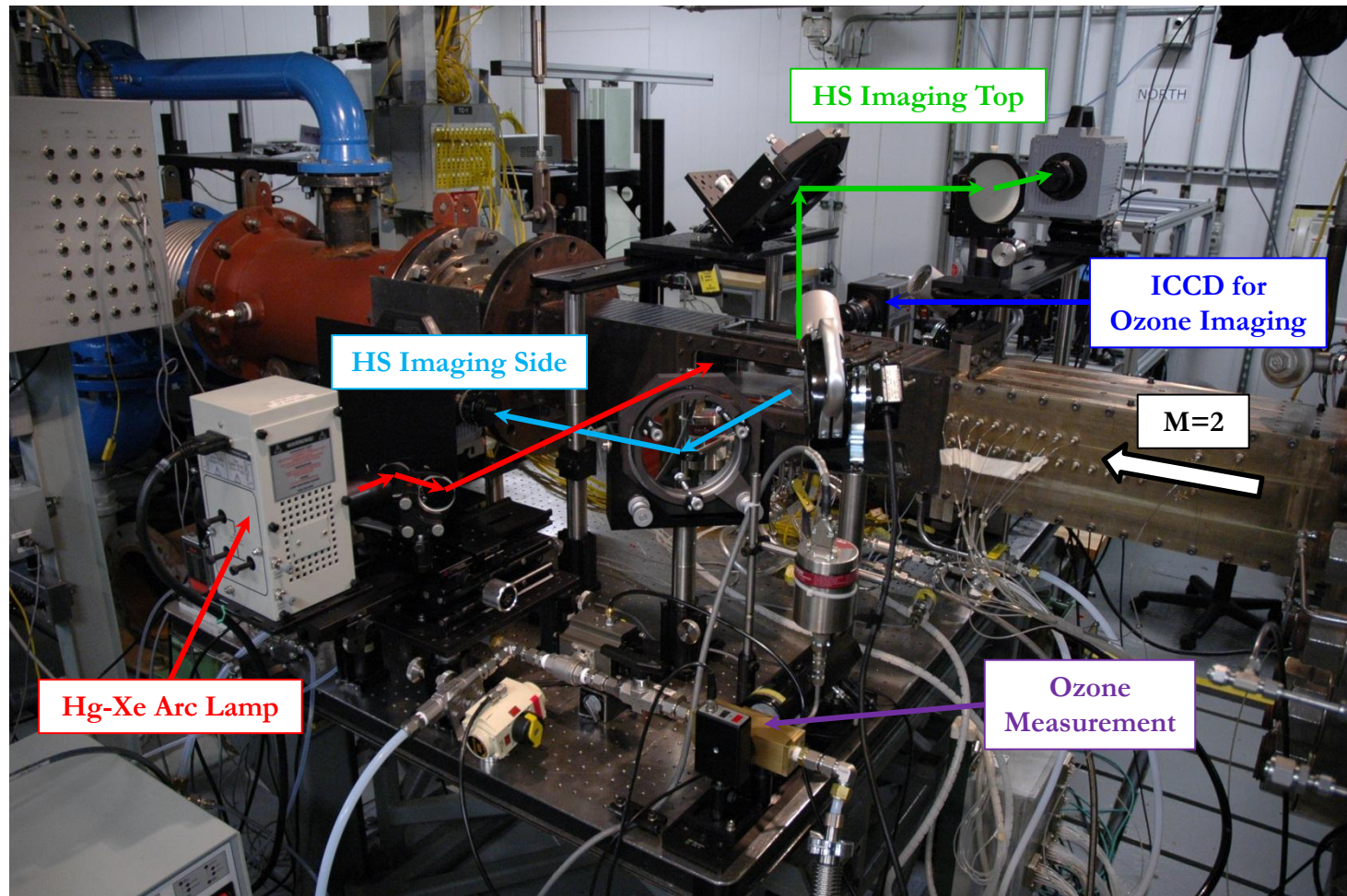


RC-19 Optical Setup: 100-kHz chemi imaging + O_3 absorption imaging



Flame Speed Enhancement by O_3

Effect of O_3 in Cavity – in M-2 Crossflow



RC-19 Windtunnel Facility



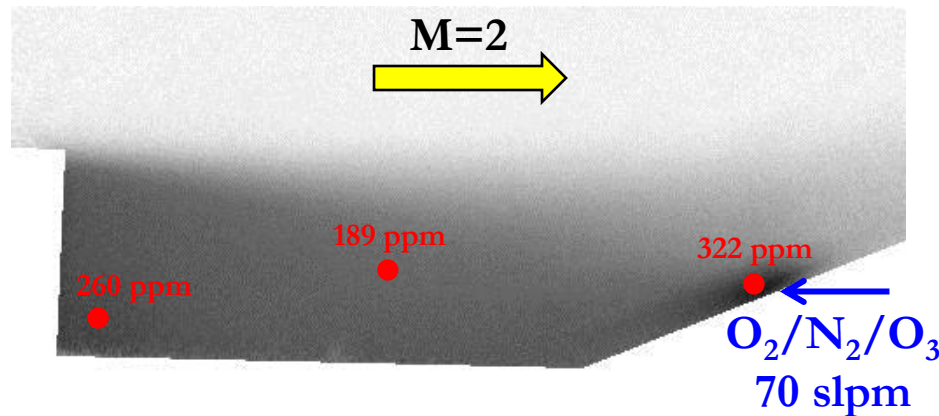
Flame Speed Enhancement by O_3

Effect of O_3 in Cavity – in M-2 Crossflow

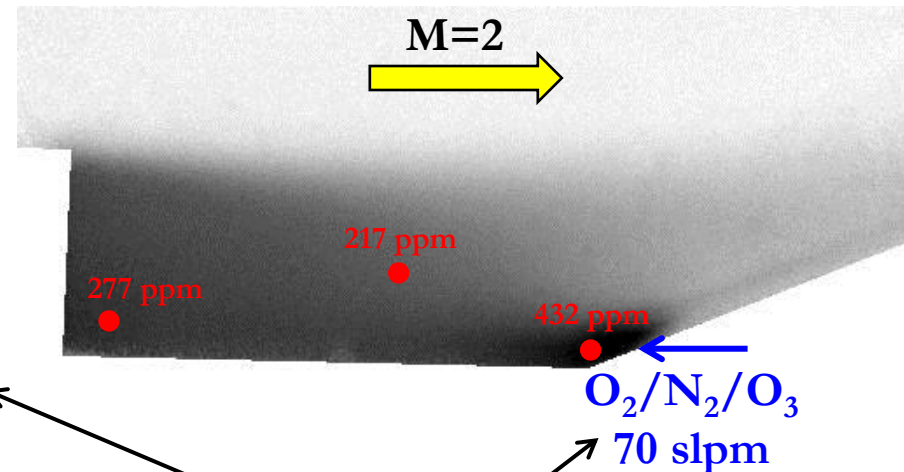


Average O_3 Concentration
Less More

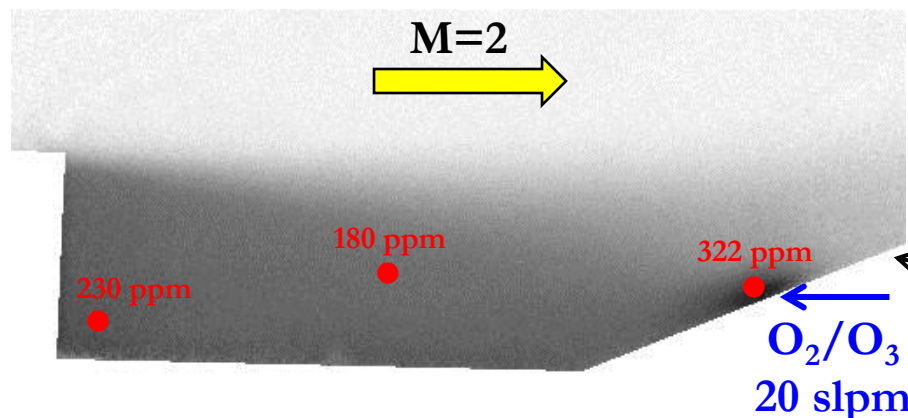
Injection from Middle Row in Cavity Ramp



Injection from Bottom Row in Cavity Ramp



Upstream $X_{O_3} = 3,850$ ppm

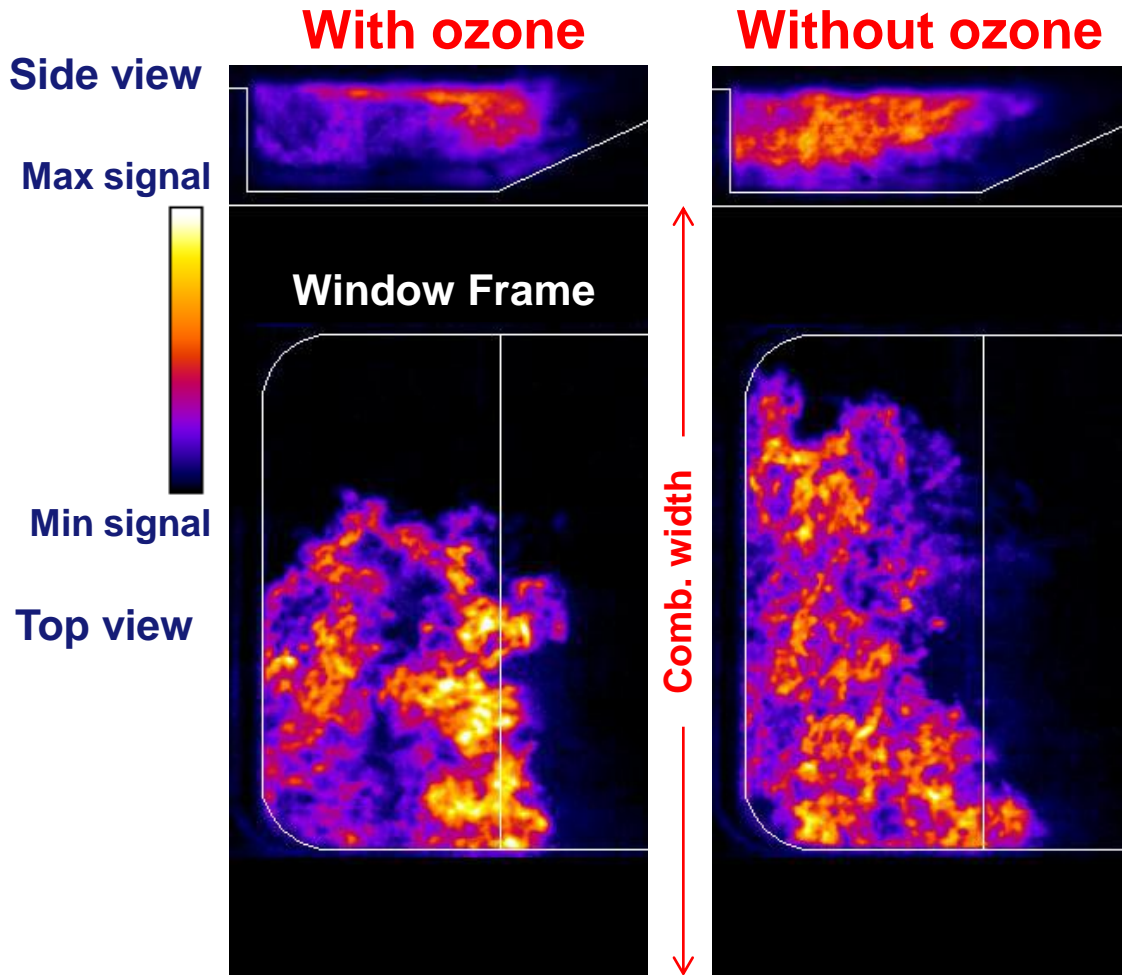


Upstream $X_{O_3} = 13,100$ ppm



Flame Speed Enhancement by O_3

Effect of O_3 in Cavity – in M-2 Crossflow



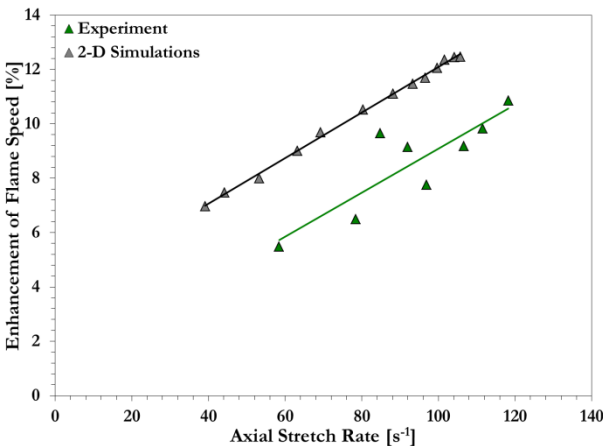
- Basics:
 - Spark ignition from two igniters
 - C_2H_4 and O_3 from separate ports on ramp face (as shown above)
 - $P_0 = 4.8$ atm; $T_0 = 600$ K
 - Image ignition at 100 kHz!
 - Top & side views
- Any difference? None that we can tell (based on several tests)
 - **Need much more O_3 in cavity to enhance flame speed**



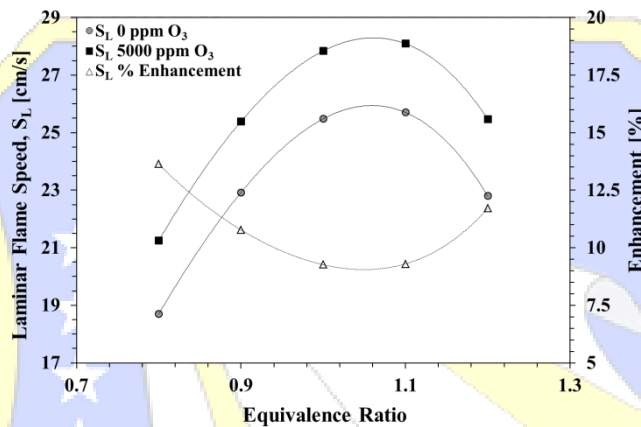
That's all Folks



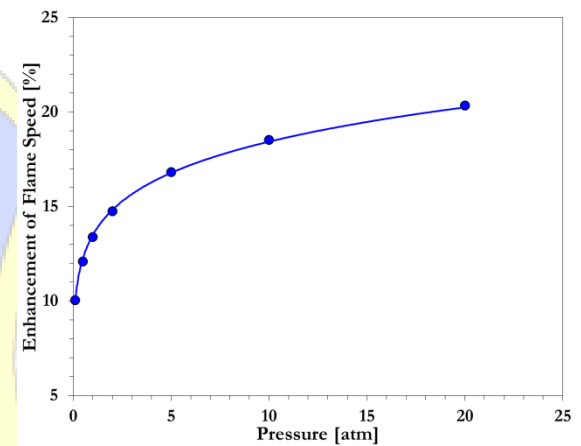
Increased Enhancement with Increased Stretch



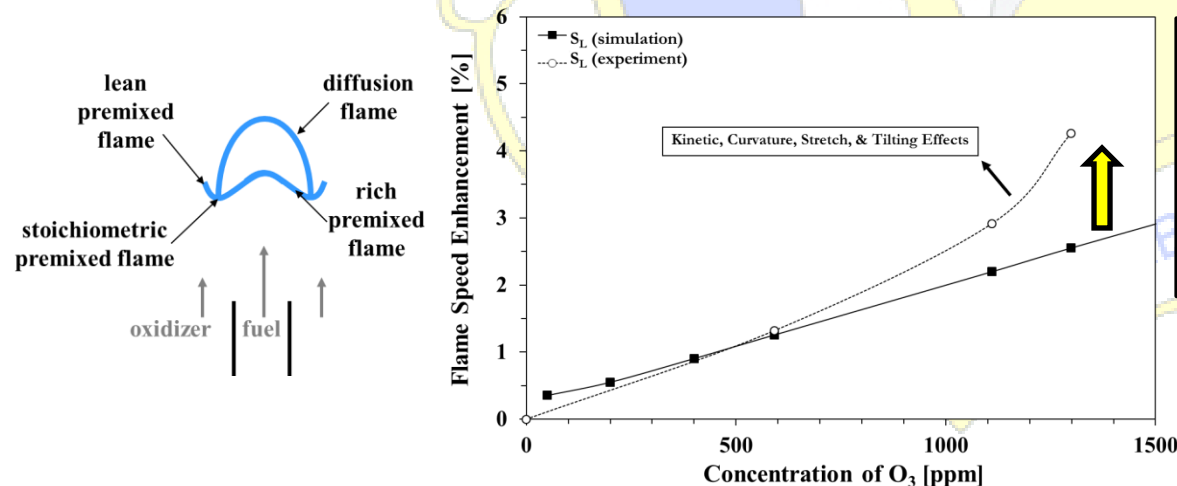
Increased Enhancement for Off-Stoichiometric Equivalence Ratios



Increased Enhancement with Increased Pressure



These Phenomena Have Already Manifested Themselves in Previous Tribrachial Flame Experiments



- Evidence from bench-top experiments indicate that flame speed should be enhanced in a turbulent flow and also possibly at higher pressures



Role of Sub-Breakdown E-Fields

Ionic Wind / Body Force Comparison



- If a cathode sheath forms, $n_i \gg n_e$. We can rewrite for the ionic wind-induced body force on the flame across the cathode sheath neglecting contributions from electrons:

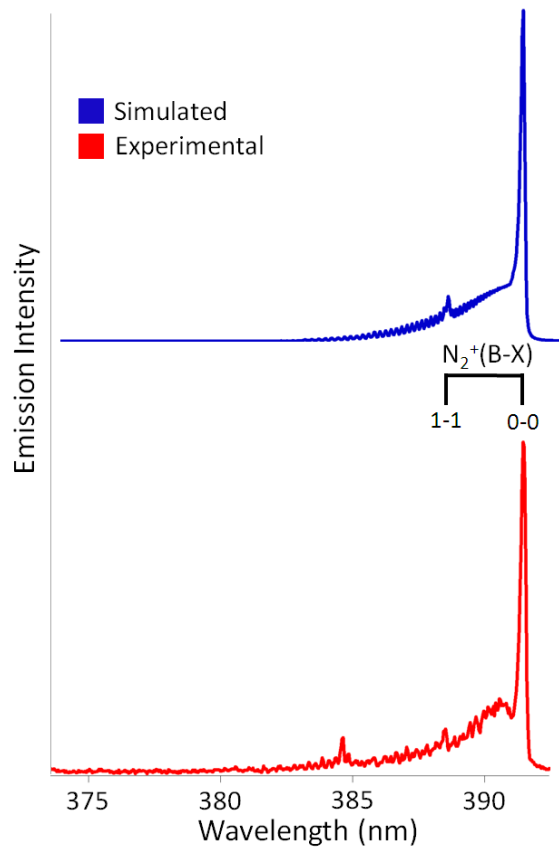
$$f = E \cdot e \cdot n_i = E \cdot \frac{I}{V_d}$$

where f = body force per area, E = electric field strength, e = charge, n_i = total number of ions, I is the current, and v_d = ion drift velocity

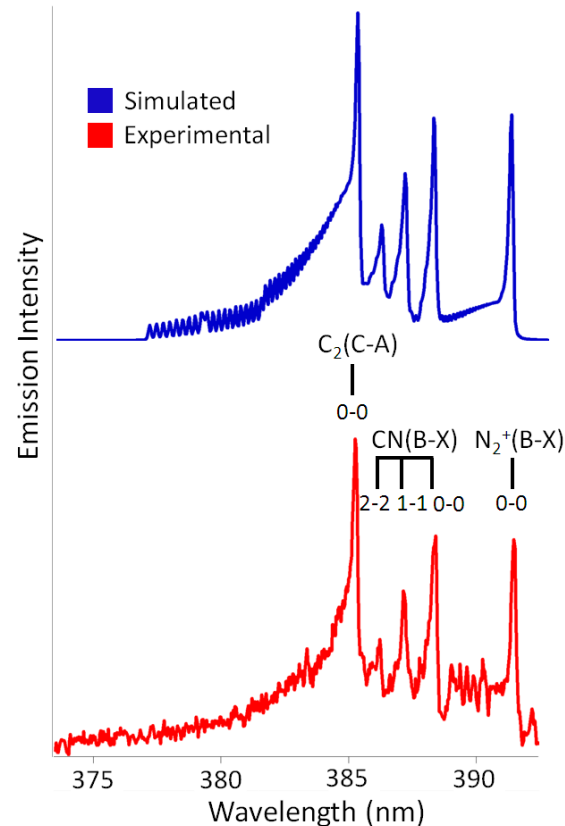
- Provides a body force per unit area of about 500 N/m² localized along reaction zone (200 μm^+) near cathode
- Suggests that disturbances seen near burner head may be due to collisional interactions between ions and neutral gas
- Magnitude of effects would be proportional to the electric field strength, ion current density, and applied pulse width time



REMPI-Assisted Gas Breakdown



Emission spectra in air during initial arc with $\lambda_{\text{laser}} = 287.5 \text{ nm}$



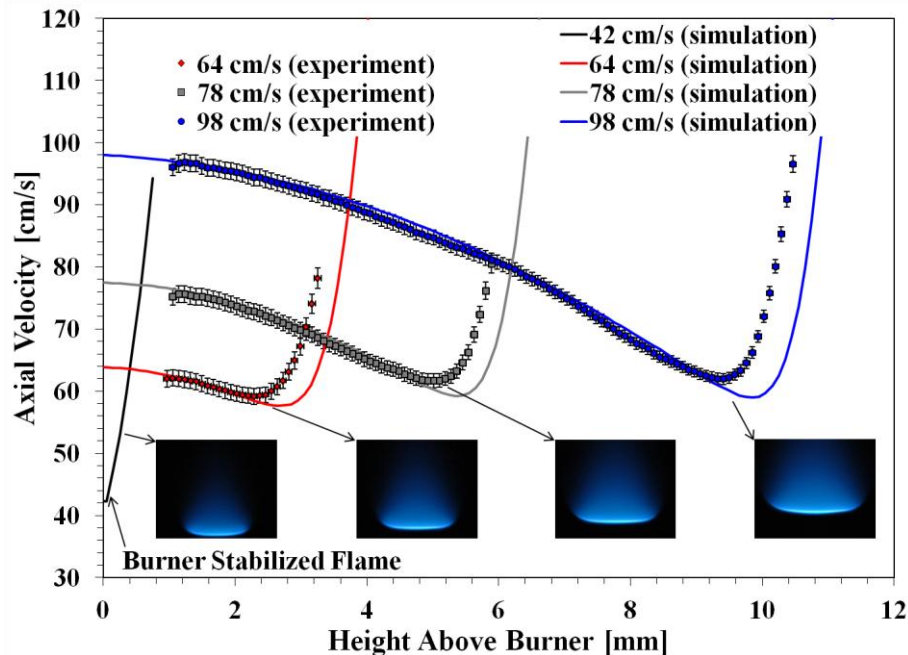
Emission spectra in C_3H_8 -air during initial arc with $\lambda_{\text{laser}} = 266 \text{ nm}$: breakdown of fuel indicated by C_2 and CN bands



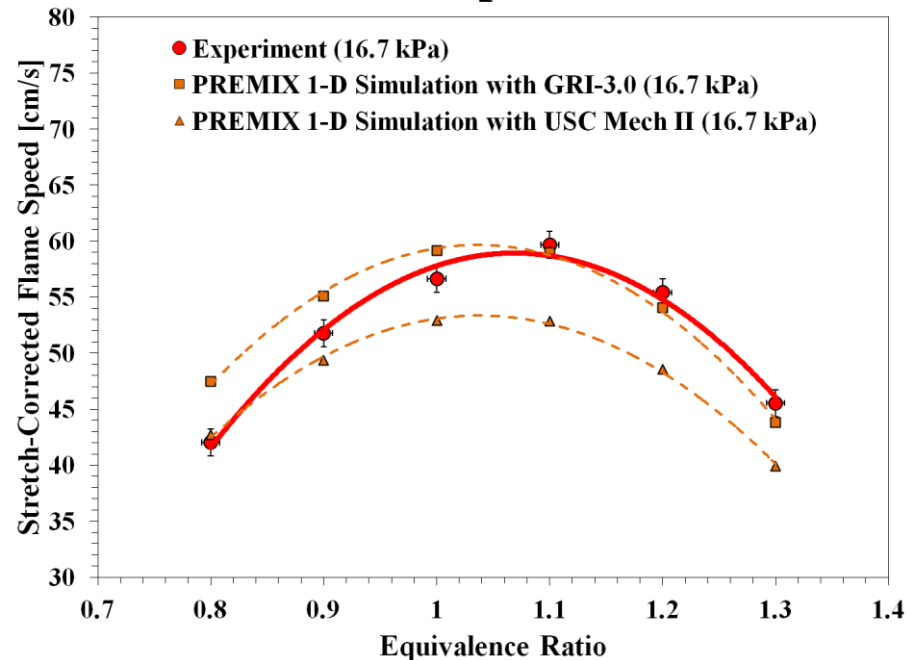
Characterization of Burner Platform with CH₄-Air



PIV and 2-D Simulations



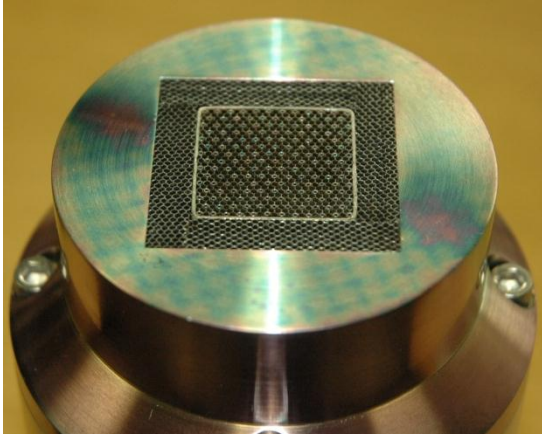
Flame Speeds



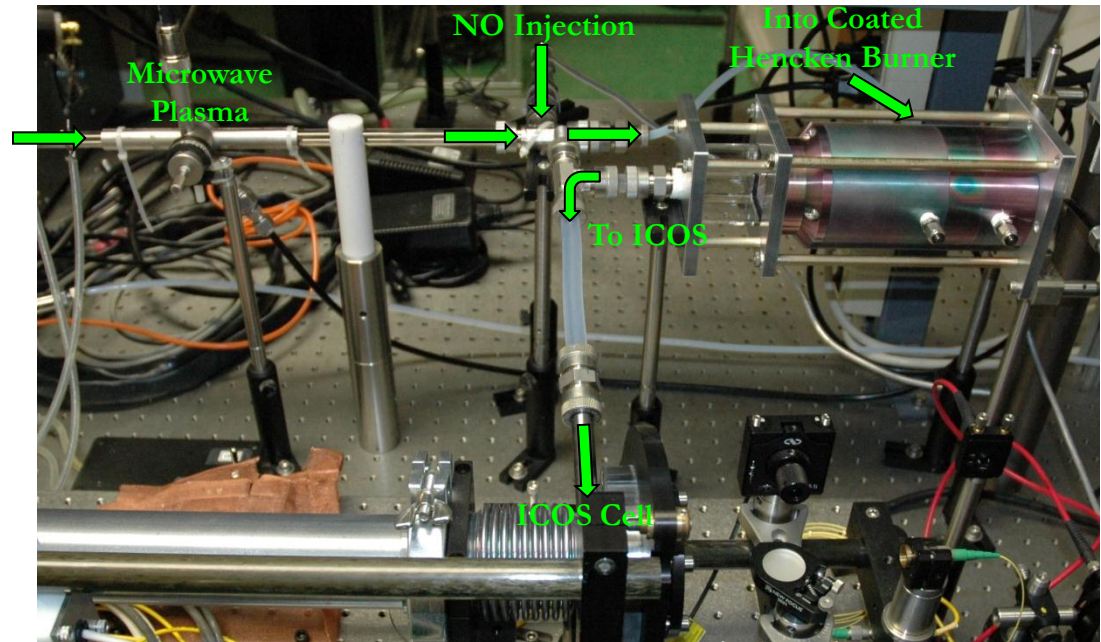
- Flame speed can be quantified with PIV
 - Change in flame liftoff height also gives good indication
- Good comparison between measurements and simulations, but absolute flamespeed slightly off measured value

Silica Coated Hencken Burner For $\text{O}_2(\text{a}^1\Delta_g)$ Flame Studies

All Flow Surfaces of Hencken Burner Coated With Silica



1000s ppm of $\text{O}_2(\text{a}^1\Delta_g)$ at Exit of Coated Burner When Using 20% O_2 in Ar with NO Injection



Absorption Techniques

Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Intracavity Laser Absorption Spectroscopy (ICLAS)

Integrated Cavity Output Spectroscopy (ICOS)

Spatially Averaged

Emission Techniques

634 nm and 1268 nm

Spatially Averaged

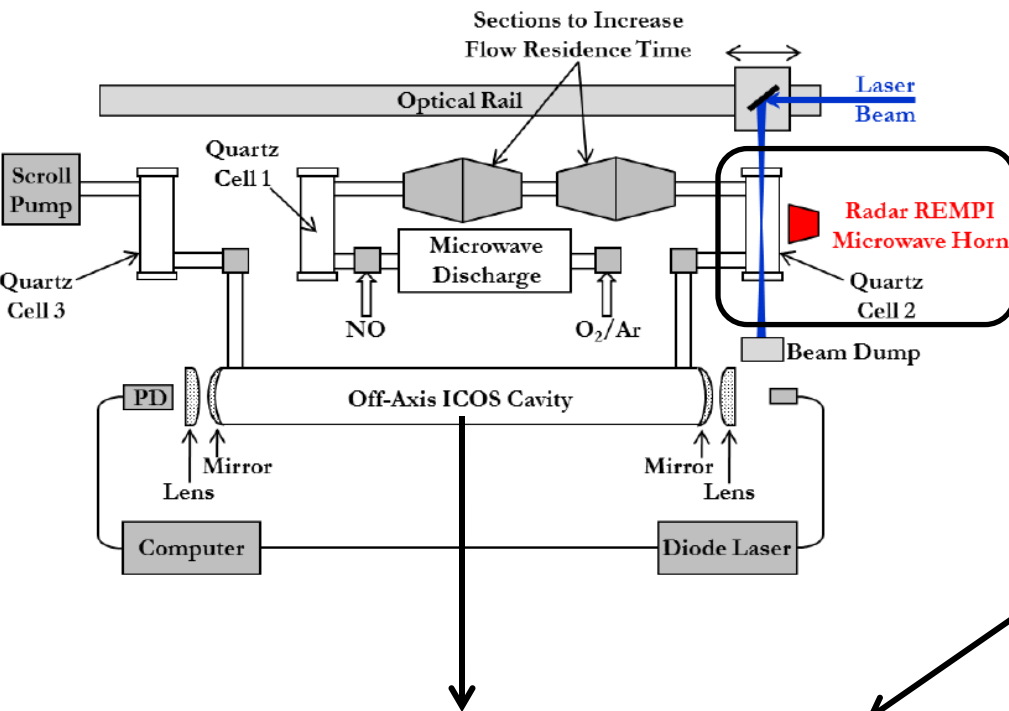
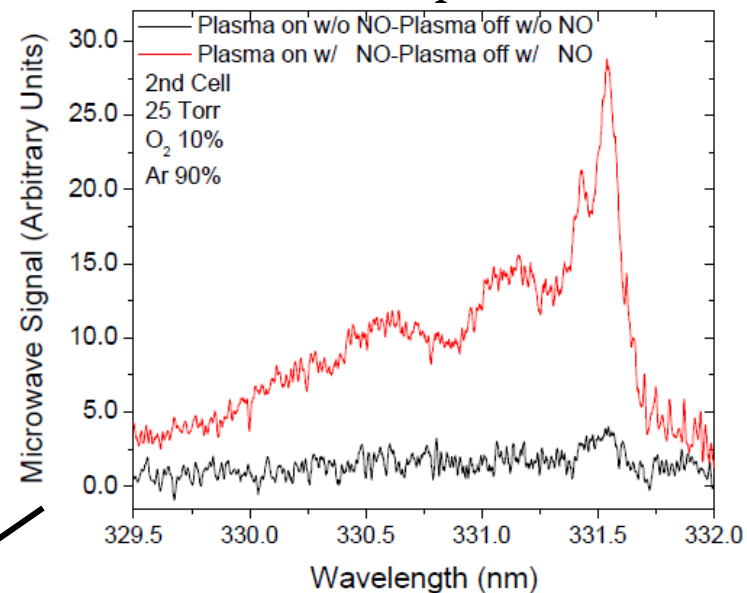
Can Require Knowledge of Quenching Species and Their Kinetics

But What About a More Spatially Resolved Measurement Above Burner Surface and Upstream of Flame?

Radar REMPI Measurements of $O_2(a^1\Delta_g)$

Two photon resonance with the O_2 transition of $d^1\Pi_g \leftarrow a^1\Delta_g$
and the subsequent one photon ionization

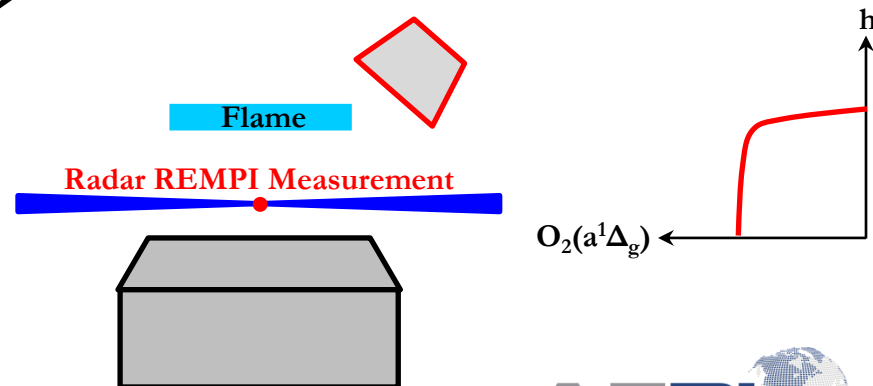
REMPI Spectrum



Detection Threshold/Sensitivity

ICOS \approx Radar REMPI

$\sim 1 \times 10^{14}$ molecules/cm³



Where Does This Bring Us With Regard to $\text{O}_2(\text{a}^1\Delta_g)$?

- New Burner System Provides a Good Platform to Interrogate Enhancement by Specific Plasma-Produced Species
- Serves Purpose to Validate Kinetic Models that are Showing Significant Enhancement But Require Experimental Validation
- New Diagnostic Techniques Being Developed for Spatially Resolved Measurements
- For $\text{O}_2(\text{a}^1\Delta_g)$, Increased Flame Speed Enhancement for Off-Stoichiometric Equivalence Ratios Confirmed, But Quantification Still Necessary

**Besides $\text{O}_2(\text{a}^1\Delta_g)$
The Other “Low Hanging Fruit”... O_3**

**Can Be Produced, Measured, and Transported Easily With Minimal Special Care
and Can Yield Significant Enhancement**

If Flame Thickness Dictates the Amount of Enhancement
then...

The Enhancement Should Increase with an Increase in Pressure

Flame Thickness $\delta \sim \frac{1}{\rho S_L}$

